

Development and Application of a Steady State Code for Supercritical Carbon Dioxide Cycles

by

David M. Legault

SUBMITTED TO THE DEPARTMENT OF NUCLEAR SCIENCE AND ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN NUCLEAR SCIENCE AND ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2006

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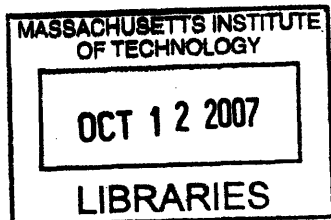
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Signature of Author:
David M. Legault
Department of Nuclear Science and Engineering
May 19, 2006

Certified by:
Dr. Michael Driscoll
Professor Emeritus of Nuclear Science and Engineering
Thesis Supervisor

Certified by:
Dr. Pavel Hejzlar
Principal Research Scientist
Thesis Co-Supervisor

Accepted by:
Dr. David Cory
Professor of Nuclear Science and Engineering
Chairman, NSE Committee for Undergraduate Students



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David M. Legault

Submitted to the Department of Nuclear Science and Engineering on May 19, 2006
In Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Nuclear Science and Engineering.

ABSTRACT

The supercritical CO₂ power conversion system is of interest for advanced nuclear reactor applications because the same efficiencies are obtained as for the most developed of the closed gas-turbine cycles (helium-Brayton), but at lower temperatures and higher pressures. The original in-house code, named CYCLES, could potentially be used by others who are researching the S-CO₂ cycle, but it has its shortcomings. In particular, CYCLES does not factor in the pressure drops due to pipes and plena. Also, for new users, it takes a significant amount of time to fully understand how to use the code. The objectives of this thesis were to modify CYCLES to ensure that pipe and plena effects were included, and to improve the readability and functionality of the code. Changes to CYCLES are included in the rewritten code, named CYCLES II, and are also documented in this thesis. Furthermore, documentation of the program input and output is given, along with a flow chart of the algorithm logic. Two applications of the code are provided to show the effect of the pipes and plena on cycle performance. In comparing the cycle efficiency with and without the effects of the pipes and plena, for a 300 MW_e S-CO₂ Brayton power conversion system, the results indicate that the net cycle efficiency drops from 49% to 45% when pipes and plena of reasonable dimensions are included in the calculations. The losses are dominated by the low pressure pipe and plena segments. However, the effects of the pipes and plena on cycle efficiency are not characteristic of the S-CO₂ cycle only. All Brayton cycles have this same issue, and the effects are worse for the helium-Brayton cycle because it operates at lower pressures.

Thesis Supervisor: Professor Michael Driscoll
Title: Professor Emeritus of Nuclear Science and Engineering

ACKNOWLEDGEMENTS

I would like to extend sincere gratitude to Professor Michael Driscoll and Dr. Pavel Hejzlar, who have been helpful in every step of the way towards the completion of my undergraduate thesis. In the beginning, Professor Driscoll was instrumental in helping me to choose the topic of my thesis. He continued to show his support by providing invaluable and prompt feedback for all the work that I presented. Pavel Hejzlar helped me to fully understand the program by mentoring me and answering any questions that I had along the way. He served as a great resource in helping me to tackle the most difficult problems I encountered with the code. I would also like to thank Jonathan Gibbs for his patience and willingness to help me model the system, and Calvin Sizer for his support throughout the entire year.

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1 INTRODUCTION

1.1 *Objective*

Vaclav Dostal, who submitted his doctoral thesis on S-CO₂ cycles in January 2004 to MIT, developed an undocumented FORTRAN code for his personal use, named CYCLES, to analyze the steady-state thermodynamics of the S-CO₂ Brayton cycle. The code proves to be useful in its calculations, but it has some disadvantages. One missing feature in the code is the calculation of pipe pressure drops. Another disadvantage of CYCLES is that it takes some time to fully become acquainted with the program. The files can be difficult to read through and understand, and the input/output files are hard to follow without a reference manual.

Extensive modifications have been made to the code, including the addition of pipe and plena effects, improved readability, and enhanced functionality. The updated code has been renamed CYCLES II. This report notes the changes made in CYCLES II and provides documentation for the code, which includes instructions for using the input and output, a general description of the algorithms, and sample applications.

1.2 *Background on S-CO₂ cycle*

Generation IV nuclear reactors are designed to be safer, more sustainable, and more economical than earlier Generation II and III designs [United States, 2002]. Closed gas turbine cycles, in particular, aim to be more sustainable and economical by achieving higher plant efficiencies. These cycles are able to achieve such high efficiencies, in part, because of their very high operating temperatures. The most developed of the closed gas turbine cycles is the helium-Brayton cycle. The problem with this cycle is that it must operate at temperatures as high as 900°C in order for it to achieve high efficiencies, which poses a challenge to the design of structural materials [Dostal, 2004]. The S-CO₂ Brayton cycle, however, is able to achieve the same efficiencies as the He-Brayton cycle, but at lower temperatures and higher pressures. Cycle components are less expensive and easier to build at very high pressures than at very high temperatures [Hejzlar, 2005], so these operating conditions can actually be advantageous. As shown in Figure 1.1, the S-CO₂ cycle has the same cycle efficiency at 650°C that the He cycle has at 850°C. The S-CO₂ cycle also operates at higher power densities, which allows for a more compact and less expensive design of the turbomachinery. An example of the MIT version of a 300 MW_e S-CO₂ power conversion system is shown in Figure 1.2.

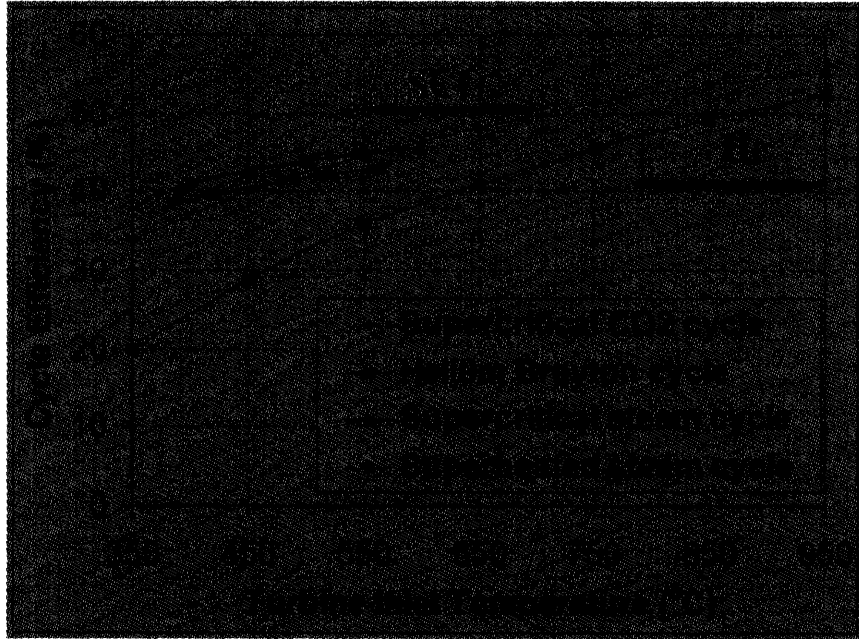


Figure 1.1: A comparison of cycle efficiencies at different operating temperatures
(Source: Hejzlar, 2005)

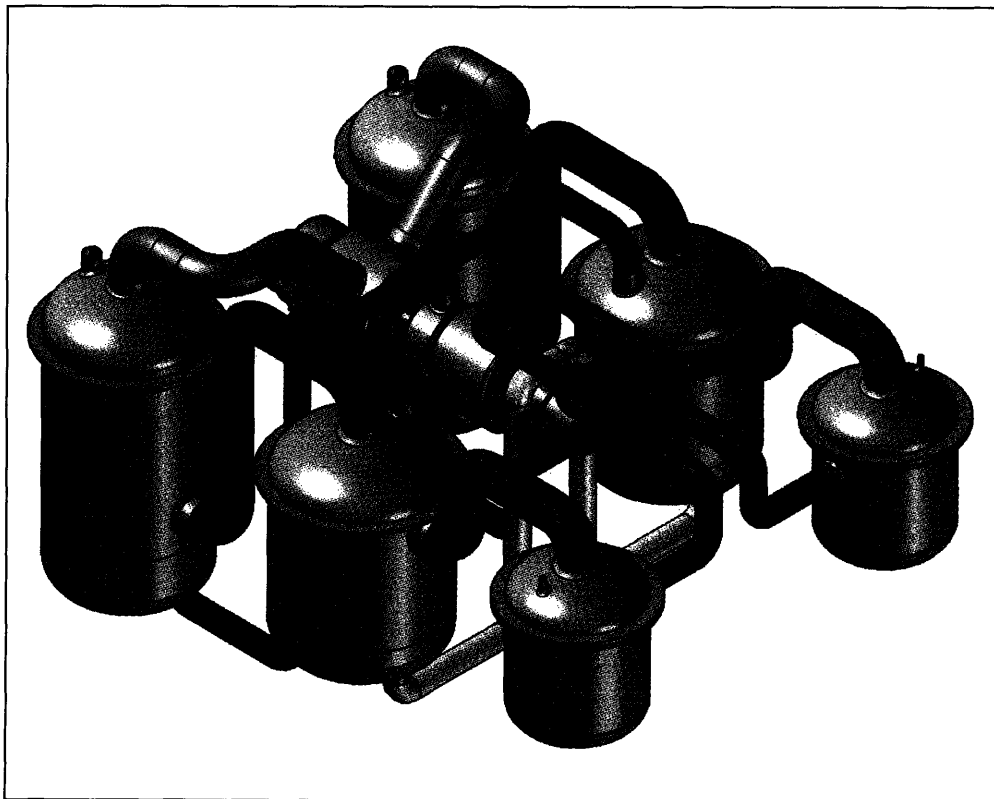


Figure 1.2: Integrated layout of S-CO₂ cycle power conversion unit

2 CHANGES MADE TO CYCLES

2.1 Structure and readability

One disadvantage of CYCLES is that it can take a while for a first-time user to become acquainted with the code. A focus of the rewritten code, CYCLES II, was to make the code easier to understand by minimizing the familiarization time. To do this, steps were taken to make the code structure less redundant and more logical. Variable names were changed to more easily recognizable names and grouped into derived-type structures, according to cycle component. In addition, Dostal's CYCLES code is written in FORTRAN77, while most of the rewritten code is written in FORTRAN90.

Common blocks

Common blocks are a way to make variables accessible within each of the subroutines. Essentially, they are used to globalize variables within the program. As an example from CYCLES, a common block is written as:

```
real*8:: viscd(1000,1000), condd(1000,1000), cpd(1000,1000)
real*8:: dmmnd(1000,1000), hpt(1000,1000), tab(5,4)
integer:: itab(5,2)

common /tables/ viscd,condd,cpd,dmmnd,hpt,tab,itab
```

In this example, the variables are first declared as “real” or “integer” type, and then specified in a common block below the declaration (The meaning of the variables is not important in this example; for a complete description of input and output parameters used in the code, refer to the code documentation in Chapter 3). The common block name is “tables”, and the values following are the common block variables. The CYCLES code was written using common blocks throughout, but CYCLES II minimizes the use of common blocks and places global variables in a module. A module is a portion of the code that contains definitions that can be used by different program units. As an example from CYCLES II, the module “modGlobalVariables” is written as:

```
MODULE modGlobalVariables
  REAL(KIND=8), DIMENSION(1000,1000) :: viscd,condd,cpd,dmmnd,hpt
  REAL(KIND=8), DIMENSION(5,4) :: tab
  INTEGER, DIMENSION(5,2) :: itab
  .
  .
  .
END MODULE
```


The definitions within the module can be used in other program units by typing “use modGlobalVariables”. For example, the variables listed above are used in the main program unit by typing the following:

```
PROGRAM cycles2  
  USE modGlobalVariables  
  .  
  .  
  .  
END PROGRAM
```

Now, all the definitions contained within “modGlobalVariables” are contained within “main”. By using a global variables module, it eliminates the need to have several lines of common blocks stated at the beginning of program units. Also if changes need to be made to these global variables, the change can be made in just the module. Using the common blocks method, each of the common blocks would need to be located and changed individually.

Variable names

Many of the variables in CYCLES are difficult to recognize when initially reading the code. To fully be acquainted with the notation, it takes time working with the code and reading the `CyclesNew.doc` reference document. As an example, the notation `Dostal` uses for the temperature state points in the high-temperature recuperator are stored in a matrix called “`trl`”. The ‘t’ in “`trl`” stands for temperature, the ‘r’ stands for recuperator, and the ‘l’ stands for low-temperature. The values of the temperature state points in the LTR are defined as follows:

<code>trl(1)</code>	inlet temperature of the cold side (°C)
<code>trl(2)</code>	outlet temperature of the cold side (°C)
<code>trl(3)</code>	(not used)
<code>trl(4)</code>	inlet temperature of the hot side (°C)
<code>trl(5)</code>	real outlet temperature of the hot side (°C)
<code>trl(6)</code>	ideal outlet temperature of the hot side (°C)

The same format is used for the LTR pressure (`prl`), enthalpy (`hrl`) and other parameters. In CYCLES II, the variables are grouped into derived-type structures, according to cycle component. A derived-type structure is used to group variables into a common record. For example, the temperature state points in the LTR are stored in the derived-type structure called “`ltr`”. The values of the temperature state points in the LTR are defined as follows:

<code>ltr.TinCold</code>	inlet temperature of the cold side (K)
<code>ltr.ToutCold</code>	outlet temperature of the cold side (K)
<code>ltr.TinHot</code>	inlet temperature of the hot side (K)
<code>ltr.ToutHot</code>	real outlet temperature of the hot side (K)

ltr.ToutHoti ideal outlet temperature of the hot side (K)

As shown, a variable name such as “ltr.TinCold” is easier to recognize than “trl(1)” as the inlet temperature of the cold side of the LTR. The five different derived-type structures in the program are “ltr”, “htr”, “pre”, “mcomp”, “recomp”, and “turb” for the low-temperature recuperator, high-temperature recuperator, main compressor, recompressing compressor, and turbine, respectively. The CYCLES code stores numbers into the temperature variables in degrees Celsius, while the CYCLES II code stores numbers into temperature variables in Kelvin. Some examples of other variables used in the code under the derived-type structure are:

mcomp.Pin inlet pressure of the main compressor (kPa)
mcomp.Pout outlet pressure of the main compressor (kPa)
turb.eta efficiency of the turbine
pre.Pdrop pressure drop in the precooler (kPa)

A list of some other variable names that were changed to more easily recognizable names in CYCLES II is given in Table 2.1.

Table 2.1: Listing of a few variable name changes in rewritten code

Old Name	New Name	Description
rmfl	mdotTotal	Total mass flow rate (kg/s)
dprechl	dP_LTRhot	Pressure drop, hot stream of LTR (kPa)
dprechl	dP_LTRcold	Pressure drop, cold stream of LTR (kPa)
dprechh	dP_HTRhot	Pressure drop, hot stream of HTR (kPa)
Dprecch	dP_HTRcold	Pressure drop, cold stream of HTR (kPa)

Commenting

The commenting within CYCLES is more complete in some areas of the code than others. The areas that contain a fair amount of commenting are the subroutines “compress”, “expand”, “PCHEvol”, and “precooler”. Each describes what the subroutine performs, as well as a list defining the input and output variables within the call. For example, the beginning of the subroutine “precooler” contains the following comments

```
!This subroutine calculates the performance of a preccooler...
! hhh - working fluid enthalpy hot end (kJ/kg) - input
! hhc - working fluid enthalpy cold end (kJ/kg) - input
! rmflf - mass flow rate of the working fluid (kg/s) - input
! rmflw - mass flow rate of cooling water (kg/s) - output
! phh - working fluid pressure hot end (kPa) - output
! phc - working fluid pressure cold end (kPa) - input
! pumpwork - thermal pumping power of cooling water... - output
! twc - cooling water temperature cold end (oC) - input
! twh - cooling water temperature hot end (oC) - output
```

The function of the subroutine is given first, followed by a list of the parameters with definitions for each. Notice that the input parameters and output parameters are given in

no particular order. CYCLES II builds on the commenting of CYCLES to include new parameters that have been added to the code. In addition, the input parameters are also separated from the output parameters and the order of the parameters is preserved within the call. That is, the call lists all the input parameters first, then all the output parameters, instead of switching between the two. An abbreviated example of the commenting within the beginning of the “precooler” subroutine of CYCLES II is

```

!INPUT parameters in subroutine call:
!   twin1 -- inlet temperature H2O stream (K)
!   hhh -- working fluid enthalpy hot end (kJ/kg)
!   hhc -- working fluid enthalpy cold end (kJ/kg)
!   rmflf -- mass flow rate of the working fluid (kg/s)
.
.
.

!OUTPUT parameters in subroutine call:
!   rmflw -- mass flow rate of cooling water (kg/s)
!   phh -- working fluid pressure hot end (kPa)
!   pumpwork -- thermal pumping power of cooling water...
!   twout -- outlet temperature H2O stream (K)
!   vouth -- average velocity of fluid at outlet, hot stream (m/s)

```

The same style of commenting, which describes the function of the particular block of code, as well as the definitions of the parameters within, is included within other areas of CYCLES II. The “readHX” and “output” subroutines and the “main” program block include such commenting, for example. Comments are also more extensively given within the body of each block of code in CYCLES II. It is considerably easier to comprehend the program when clear commenting is used throughout the program.

2.2 Pipe and plena pressure drops

CYCLES does not take into account the effects of pipe and plena losses. That is, all state points at the inlet of the pipes (temperature, pressure, enthalpy, etc.) are the same for the outlet of the pipes. CYCLES II takes into account losses in both the pipes and the plena, which allows for a more accurate value of the cycle parameters (e.g., cycle efficiency). The inputted data for each pipe (or plenum) includes the pipe diameter, pipe area, pipe length, form loss coefficient, and roughness of the inside of the pipe. The rewritten code also allows for the input of pipes with multiple sections. The pipe model is described in detail in Hejzlar et al., 2006.

2.3 Zigzag and plate pattern options

The heat exchanger analysis in both CYCLES and CYCLES II is based on the design of Heatric™ PCHE heat exchangers. The PCHE designs include both straight and zigzag channels, but CYCLES only allows for straight channel calculations to be made. Heat

exchangers with zigzag channels are smaller in volume, cost less, and have higher heat exchanger effectiveness [Driscoll, 2004]. CYCLES II was modified to allow calculations to be made for either straight or zigzag channels.

Another aspect of CYCLES is that it only performs heat exchanger calculations for plates that are stacked in the repeating pattern: hot/cold/hot/cold. CYCLES II allows for calculations of this pattern as well as the following patterns: 1 hot plate followed by 2 cold plates or 2 hot plates followed by 1 cold plate. The heat exchanger model is described in detail in Hejzlar et al., 2006.

2.4 Input

CYCLES

The input for CYCLES includes a general input file with overall cycle data, three heat exchanger input files, and several table creation input files. The overall cycle and heat exchanger input files contain one data input per line. An example of an overall cycle input file, `input.txt`, is:

```
0
0
20000d0
40.2d0
2.6d0
650.0d0
32.0d0
0.91d0
0.90d0
0.94d0
20.0d0
500.0d0
1
1.0d-2
```

This file contains no commenting, only the data values. The same format is given to the heat exchanger files, `ltr`, `htr`, and `pre`. An explanation of the data contained in the input file is given in `CyclesNew.doc`.

The input data is read within the LTR, HTR, and PRE subroutines, which are called multiple times in the convergence algorithm. Since the input data does not change, this is redundant and increases the code run time.

CYCLES II

For CYCLES II, instead of having `input.txt`, `ltr`, `htr`, and `pre` as separate data files, they are all combined into one file, `HXdata.txt`. The data from the four files are appropriately labeled within the file `HXdata.txt`. Also, a description of the input is given within the file, on the same line as the data it is referencing. The descriptions are given after the comment symbol `!` in FORTRAN. An abbreviated example of the new input is:

```
Main Cycle Input Data
false          !Table creation trigger...
false          !Case trigger...
20000d0        !Compressor outlet pressure (kPa)
40.2d0         !Cycle thermal power (MWt)
.
.
.
HTR data
strihc         !Channel type...
0.002          !hot channel diameter (m)
0.002          !cold channel diameter (m)
0.0015         !hot plate thickness (m)
.
.
.
LTR data
strihc         !Channel type...
0.002          !hot channel diameter (m)
0.002          !cold channel diameter (m)
0.0015         !hot plate thickness (m)
.
.
.
PRE data
strihc         !Channel type...
0.002          !hot channel diameter (m)
0.002          !cold channel diameter (m)
0.0015         !hot plate thickness (m)
.
.
.
```

All of the input reads have been removed from the LTR, HTR, and PRE subroutines—the data is read in one subroutine for simplicity and also to reduce redundancy.

The input file contains pipe input data. CYCLES did not calculate pipe losses, and therefore did not have an input file for the pipes. Each pipe path is given a number, according to the pipe layout scheme shown in Figure 2.1. A description of the pipe paths is given in Table 2.2. Note that the reactor can also be an intermediate heat exchanger (IHX) when modeled as an indirect cycle.

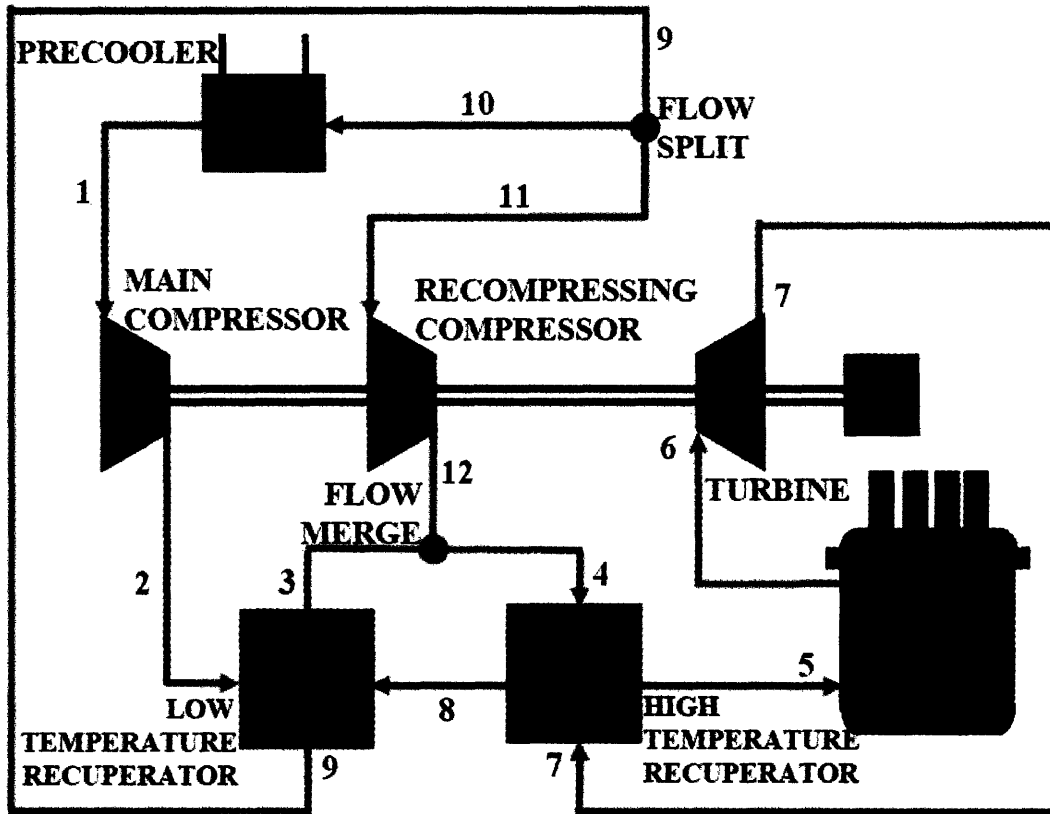


Figure 2.1: Pipe Layout Scheme (Adapted from: Hejzlar et al., 2006)

Table 2.2: Pipe Layout Scheme Description

Pipe Path Number	Description
1	precooler to Main compressor
2	Main compressor and LTR
3	LTR to flow merge tee junction
5	LTR to flow merge tee junction
4	flow merge tee junction to HTR
5	HTR to IHX
6	IHX to turbine
7	turbine to HTR
8	HTR to LTR
9	LTR to flow split junction
10	flow split junction to precooler
11	flow split junction to recompressing compressor

The pipe data given in the `HXdata.txt` includes the diameter, cross-sectional area, length, form loss coefficient, and roughness. An abbreviated example of the pipe input data is given in Figure 2.2. A more detailed description of this pipe input data, including a description of the terms, as well as the other input data contained in `HXdata.txt` is provided in Section 3.2: Pipe and plena input data.

Pipe data (12 sets)											
IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip) (m)				
precooler to main compressor											
1	4	6	0.1576	0.019500	0.2800	0.04	1.0E-04	!precooler outlet plenum LP			
1	830	1	0.0030	0.000090	0.0050	1.20	1.0E-04	!precooler outlets LP			
1	1	1	0.3500	0.140000	0.3000	0.40	1.0E-04	!precooler side plenum LP			
1	1	1	0.1524	0.0182	3.33	0.82	1.0E-04	!pipe to main compressor			
main compressor to LTR											
2	3	1	0.1524	0.018200	1.17	1.716	1.0E-04	!pipe to LTR			
2	1	1	0.3048	0.072966	0.3000	0.40	1.0E-04	!LTR inlet side plenum HP			
2	6	6	0.1151	0.010410	2.0000	0.70	1.0E-04	!LTR inlet distribution plena			
HP											
.											
.											
.											
From turbine to HTR											
7	4	1	0.4064	0.1297	0.3600	1.12	1.0E-04	!Pipe From turbine to HTR			
7	1	1	0.3500	0.140000	2.5000	0.40	1.0E-04	!HTR inlet side plenum LP			
7	4192	1	0.0030	0.000090	0.0050	1.20	1.0E-04	!HTR inlets LP			
7	6	6	0.2811	0.048750	0.0800	0.40	1.0E-04	!HTR inlet plenum LP			
.											
.											
.											
From LTR to split T junction											
9	4	6	0.2228	0.039000	0.2800	0.40	1.0E-04	!LTR outlet plenum LP			
9	3330	1	0.0030	0.000090	0.0050	1.20	1.0E-04	!LTR outlets LP			
9	1	1	0.3500	0.140000	2.0000	0.40	1.0E-04	!LTR outlet side plenum LP			
9	1	1	0.2540	0.0507	1.83	0.12	1.0E-04	!Pipe From LTR to split T			
.											
.											
.											

Figure 2.2: Example of pipe input data contained in HXdata.txt

2.5 Output

CYCLES

The output for CYCLES is included in three files. One of the files, called `res.txt`, contains a summary of results, including overall and component efficiencies, work of the turbomachinery, heat transfer in the heat exchangers, and pressure drops in each of the components. The second file, `cycres.txt`, contains data for all the state points, including inlet and outlet temperatures, pressures, enthalpies, and entropies. The last file, `optimres.txt`, contains the results of cycle optimization.

All of the data of the file `res.txt` is written on two lines, with the name of the output data on the first line, and the value on the data on the second line. In all, forty values are given across the two lines. The two lines spanned just over 360 columns. An abbreviated example of the first seven values of `res.txt` is:

pres-ra	eta1	eta2	eta-net	el-pow	th-pow	pumpwork...
2.600	50.787	50.770	50.696	304.691	599.942	541.684...

As shown, the descriptions of the variables above are abbreviations without units, but can be referenced in `CyclesNew.doc`.

The file `cycres.txt` contains five rows of numbers, with temperature points in the first column, pressure points in the second, enthalpy in the third, entropy in the fourth, and the fifth column is unused. The rows are grouped together by component: main compressor, recompressing compressor, turbine, low-temperature recuperator, and high-temperature recuperator. The data values are unlabeled, but can be referenced in `CyclesNew.doc`. An example of the output data in this file for the low-temperature recuperator is

60.9186	20000.0000	326.8039	0.0000	0.0000
156.3891	19991.1740	533.5467	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
169.1683	7780.7524	605.2896	0.0000	0.0000
68.6519	7699.1980	477.1823	0.0000	0.0000
60.9186	7699.1980	464.0053	0.0000	0.0000

The first line contains values for the inlet on the cold side of the LTR, the second line has values for the outlet on the cold side, the third line is unused, the fourth has values of the inlet on the hot side, the fifth has values for ideal outlet conditions on the hot side, and the last line has values for the real outlet conditions.

CYCLES II

The output for CYCLES II combines important data from `res.txt` and `cycles.txt` into one file, `output.txt`. The output file is divided into five different sections: cycle schematic, heat exchangers, further heat exchanger data, turbomachinery, pipes, and overall cycle data. All numbers are explicitly labeled and include units (in the case where a number is dimensionless, no units are given). An example of the new output is shown in Figure 2.4.

Cycle Schematic – This section is provided as a visual to see where each of the components and pipes lies in relation to one other. Descriptions of the pipe path numbers, similar to those in Table 2.2, are given next to the schematic.

Heat Exchangers – This section provides important cycle state point parameters for the high-temperature recuperator, low-temperature recuperator, and precooler. Hot and cold side parameters are shown for each heat exchanger. Parameters include inlet and outlet temperatures and pressures, pressure drops, heat transfer rates, mass flow rates, outlet velocities, and Reynolds numbers. All values refer to the *active length* or *core* of the heat exchangers, which does NOT include the plena.

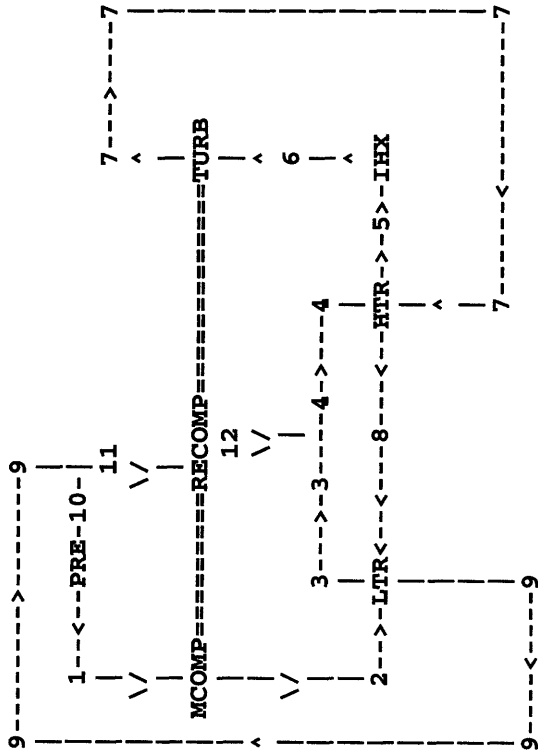
Further Heat Exchanger Data – This section provides further heat exchanger parameters that pertain to the whole heat exchanger and not a particular side. Parameters include the overall heat transfer coefficient and effectiveness, as well as the module dimensions and the number of hot and cold channels. All values refer to the *active length* or *core* of the heat exchangers, which does NOT include the plena.

Turbomachinery – This section provides cycle state points parameters for the main compressor, recompressing compressor, and the turbine. Parameters include inlet and outlet temperatures and pressures, pressure drops, power values, mass flow rates, efficiencies, and pressure ratios.

Pipes – This section provides important cycle state points for each of the pipes. Parameters include inlet and outlet temperatures and pressures, pressure drops, and outlet velocities.

Overall Cycle – This section provides overall cycle data. Parameters include efficiency, heat transfer rate in, heat transfer rate out, net power, pump power, minimum temperature difference in the heat exchangers, reactor pressure drop, overall flow rate, and fractional flow rate to the main compressor.

CYCLE SCHEMATIC



- ip - pipe path number
- =1 precooler to main compressor
 - =2 Main compressor and LTR
 - =3 LTR to flow merge tee junction
 - =5 LTR to flow merge tee junction
 - =4 flow merge tee junction to HTR
 - =5 HTR to IHX
 - =6 IHX to turbine
 - =7 turbine to HTR
 - =8 HTR to LTR
 - =9 LTR to flow split junction
 - =10 flow split junction to precooler
 - =11 flow split junction to recomp
 - =12 recomp to flow merge tee junction

HEAT EXCHANGERS

	Tin (C)	Tout (C)	Pin (kPa)	Pout (kPa)	dP (kPa)	Q (MWT)	mDot (kg/s)	vout (m/s)	Re
HTR hot	528.21	166.40	7733.7	7733.1	0.595	-82.2	197.4	0.623	1700.5
HTR cold	160.56	486.62	19914.3	19914.0	0.230	82.2	197.4	0.233	1318.7
LTR hot	166.31	72.62	7709.5	7709.0	0.559	-23.5	197.4	0.414	2629.0
LTR cold	60.90	160.63	19950.1	19950.0	0.086	23.5	109.9	0.077	497.3
PRE CO2	72.49	32.00	7692.4	7692.3	0.118	-19.4	109.9	0.071	2837.9
PRE H2O	20.00	31.13					417.3	0.004	279.6

FURTHER HEAT EXCHANGER DATA

	U (W/m2-K)	eff	Mod Height (m)	Mod Width (m)	Mod Length (m)	Core Vol (m3)	Passages H	Passages C
HTR	59.79	0.98	1.00	0.43	2.30	66.86	3985324.	3985324.
LTR	86.91	0.86	1.00	0.50	2.00	43.14	2959318.	2959318.
PRE	149.44		1.00	1.11	0.90	10.00	1531800.	1531800.

Figure 2.3a: Example of cycle output data contained in output.txt

TURBOMACHINERY												
	Tin	Tout	Pin	Pout	dP	W	mDot	eta	Pratio			
	(C)	(C)	(kPa)	(kPa)	(kPa)	(MWT)	(kg/s)					
Main Comp	31.85	60.95	7652.9	20000.0	-12347.1	-2.2	109.9	0.91	2.61			
Recomp	72.43	161.28	7687.0	19946.7	-12259.6	-5.1	87.4	0.90	2.59			
Turbine	649.99	528.25	19322.1	7774.8	11547.3	28.0	197.4	0.94	2.49			
PIPES												
Pipe No.	Tin	Tout	Pin	Pout	dP	vout						
	(C)	(C)	(kPa)	(kPa)	(kPa)	(m/s)						
1	32.00	31.85	7692.3	7652.9	39.4	10.1						
2	60.95	60.89	20000.0	19950.1	49.9	2.5						
3	160.63	160.61	19950.0	19941.3	8.7	3.6						
4	160.64	160.57	19941.7	19914.1	27.6	10.3						
5	486.62	486.56	19914.0	19835.2	78.9	20.1						
6	650.00	649.99	19335.0	19322.0	13.0	36.6						
7	528.25	528.21	7774.8	7733.7	41.0	13.3						
8	166.40	166.31	7733.1	7709.5	23.6	8.2						
9	72.61	72.49	7708.8	7692.1	16.8	24.2						
10	72.49	72.31	7692.1	7665.2	26.9	5.9						
11	72.49	72.46	7692.1	7687.1	5.0	10.8						
12	161.28	161.28	19946.7	19941.7	5.0	5.6						
OVERALL CYCLE												
eta1	eta2	eta-net	Q in	Q out	W net	W pump	dT min	dP reactor	Main Comp			
			(MWT)	(MWT)	(MW)	(kWe)	(C)	(kPa)	Flow Frac			
0.51	0.52	0.51	40.17	19.42	20.65	-1.08	0.00	500.00	0.56			

Figure 2.4b: Example of cycle output data contained in output.txt

2.6 Command window feedback

In CYCLES, when the program is executed successfully, the only feedback displayed to the command window is “recomp OK” after the convergence is complete. In an effort to show the user explicitly where the execution process is in the code, CYCLES II displays additional feedback to the command window. A typical execution of the program produces the following output to the command window:

```
reading file HXdata.txt...
    make sure HX length is for zigzag channels
reading completed
begin convergence
    1
    2
    3
    4
    5
    6
    7
    8
    9
    10
PRE converged
printing output to file output.txt...
printing completed
```

The command window displays when the reading of the input files begins and ends, when the convergence algorithm begins and ends, and when the printing of the output begins and ends. The numbers 1-10 indicate the location of the execution process within the convergence algorithm.

2.7 Other simplifications

Optimization

CYCLES allows one to perform calculations on the recompression cycle one of two ways [Dostal, 2005]:

- Given the precise geometry of the heat exchangers, the code calculates single point efficiency, including the temperature and pressure drops across each component.
- Given a set total volume for the exchangers, the code optimizes the dimensions (length, width, and height) of the heat exchangers that will achieve the highest efficiency.

CYCLES II only performs the single point efficiency calculation and does not allow for optimization. This option was taken out for simplification. Furthermore, now that significant experience has been accumulated, a fairly narrow range can be pre-assigned for most independent variables.

Inter-cooling and re-heating

Both inter-cooling (using multiple compressors in series) and re-heating (using multiple turbines in series) are allowable in CYCLES. CYCLES allows these options in order to make the code more general, hence applicable to different S-CO₂ cycles. All calculations were performed on the recompression cycle. Also, since neither inter-cooling nor re-heating calculations is used in this cycle, these options are removed in CYCLES II for simplification.

2.8 Chapter summary

Many changes were made in CYCLES II in order to minimize the familiarization time, enhance the accuracy of the calculations, and reduce the complexity of the code:

- Instead of using common blocks to transfer global variables between subroutines, all global variables were placed in the module “modGlobalVariables”.
- Variable names were changed to more easily recognizable names. For example, the value of the inlet temperature of the cold side of the low-temperature recuperator is stored in “ltr.TinCold” in CYCLES II, as opposed to “trl(1)” in CYCLES.
- Losses in both the pipes and the plena are taken into account in CYCLES II.
- Straight or zigzag channel heat exchangers can be calculated
- Three different plate stacking patterns are allowed
- The input files for the heat exchangers and the pipes have been consolidated into one input file. The input file is commented so that the user knows the definition of each line of data, without having to reference a manual.
- Important output parameters are printed to one easily readable output file. The file is organized by component, and parameters are labeled with a description and units.
- The command window provides more feedback while the program executes to allow the user to know what is happening during the execution process.
- Optimization, inter-cooling and re-heating options have been removed from the code for simplification.

3 CODE DOCUMENTATION – FINAL VERSION

3.1 Introduction

CYCLES II is a modified version of the code CYCLES, which was written by Vaclav Dostal for his doctoral thesis at MIT in 2004. The code analyzes the steady-state thermodynamics of the S-CO₂ Brayton cycle. CYCLES II was modified specifically for the S-CO₂ recompression Brayton cycle, which is shown schematically in Figure 2.1. All changes that have been made to CYCLES are documented in Chapter 2. The purpose of this chapter is to provide a basic overview of the program for a new user to easily get acquainted with the code. A description of the input and output for the program is provided, and a flow chart is given to understand the algorithm logic.

3.2 Input

The input data for the program is written in the file `HXdata.txt`, which contains information on the overall cycle, heat exchangers, and pipes. At the end of the file, data for optimization purposes are also supplied. This section describes the input file and all its parameters.

The `HXdata.txt` file is broken up into six sections: “Main cycle input data”, “HTR data”, “LTR data”, “PRE data”, and “Pipe data”. The actual titles of the sections are given in `HXdata.txt`, but the titles do not affect the calculations—they are read in and stored into a “dummy” variable that is never used. Each line, following the title of the section, contains one or more input parameters and a description of that input. The description always follows an exclamation mark. Anything written after the exclamation mark ‘!’ is a comment and is not read in to the program. Where applicable, units are given in the description of the variable following the exclamation mark.

A Note on Turbomachinery Efficiency

When calculating the efficiency of turbomachinery components, it is important to know if the value indicates a total-to-total or total-to-static efficiency. Essentially, when a property is referred to as “total”, such as total enthalpy, total temperature, or total pressure, it indicates that the velocity is taken into account. When a property is referred to as “static” it indicates that the velocity is not considered. Total conditions are typically used at the inlet of a turbine or compressor, but either total or static conditions can be used at the outlet [Cumpsty, 2004]. Either the difference in total-to-total enthalpies or the difference in total-to-static enthalpies can be used to calculate efficiency, which can lead to confusion if not explicitly stated which type is used. Dostal’s code uses NIST

subroutines to calculate the conditions, which do not account for velocity (source). It is therefore best to consider the efficiency input values as a total-to-static efficiency.

To distinguish between the two efficiencies, first consider a control volume around a compressor. Under steady-state conditions and when assuming no heat transfer and no change in kinetic energy, the first law reduces to:

$$\dot{W} = \dot{m}(h_1 - h_2) \quad (3-1)$$

where \dot{W} is the power required to run the compressor (W), \dot{m} is the mass flow rate (kg/s) of the working fluid, and h_1 and h_2 are the specific enthalpies (J/kg) at the inlet and outlet of the compressor, respectively. However, in some models, inlet and outlet velocities cannot be ignored. In the case where velocities are taken into account, the first law reduces to:

$$\dot{W} = \dot{m}[(h_1 - h_2) - (v_1^2 - v_2^2)/2] \quad (3-2)$$

where v indicates velocity (m/s). The enthalpy and velocity can be combined into one term, h_t , which is the total (or stagnation) enthalpy:

$$\begin{aligned} h_{t1} &= h_1 + v_1^2 / 2 \\ h_{t2} &= h_2 + v_2^2 / 2 \end{aligned} \quad (3-3)$$

If the fluid is an ideal gas, then h is equal to $c_p T$. Substituting this into the equations in (3-3) gives:

$$\begin{aligned} T_{t1} &= T_1 + v_1^2 / 2c_p \\ T_{t2} &= T_2 + v_2^2 / 2c_p \end{aligned} \quad (3-4)$$

where T_t is referred to as the total temperature. Combining equations (3-2), (3-3) and (3-4) gives:

$$\dot{W} = \dot{m}c_p (T_{t1} - T_{t2}) \quad (3-5)$$

To determine how the total enthalpies or total temperatures affect turbomachinery efficiency, we look at the efficiency of a compressor as an example, which is defined as:

$$\eta_c = \frac{\dot{W}_{ideal}}{\dot{W}_{actual}} \quad (3-6)$$

where the subscript ideal refers to the case for an isentropic compressor and the subscript actual refers to the actual conditions. If total conditions are used at both the inlet and the outlet, then the efficiency is written as:

$$\eta_{tt} = \frac{(h_{t1} - h_{t2})_{ideal}}{(h_{t1} - h_{t2})_{actual}} \quad (3-7)$$

where η_{tt} is the total-to-total efficiency, and all temperatures are denoted with a subscript 't' to indicate total values. If the total conditions are used at the inlet, but the static conditions are used at the outlet, then the efficiency changes to:

$$\eta_{ts} = \frac{(h_{t1} - h_2)_{ideal}}{(h_{t1} - h_2)_{actual}} \quad (3-8)$$

where η_{ts} is the total-to-static efficiency and the temperature at the outlet is no longer total temperature but static temperature. Equation 3-8 is the convention adopted for CYCLES II.

Main Cycle Input Data

An example of the input within the main cycle input data section is

```

Main cycle input data
0          !...Table creation trigger...
0          !...Property trigger...
20000d0   !...Main compressor outlet pressure (kPa)
40.2d0    !...Cycle thermal power (MWt)
2.6d0     !...Pressure ratio of the main compressor...
650.0d0   !...IHX outlet temperature (C)
32.0d0    !...Precooler outlet temperature (C)
0.91d0    !...Main compressor efficiency...
0.90d0    !...Recompressing compressor efficiency...
0.94d0    !...Turbine efficiency in dimensionless form
0.99      !...mechanical efficiency (couplings)
0.98      !...generator efficiency
1.00      !...frequency converter efficiency...
20.0d0    !...Cooling water inlet temperature (C)
500.0d0   !...IHX pressure drop (kPa)
1         !...Number of turbines...
1.0d-2    !...Tolerance...

```

As shown, for each line, the input parameter is given first, followed by a commented description. What follows is a more detailed description of each of the input parameters.

Table creation trigger – The table creation trigger is an integer, either '1' or '0', that determines whether or not to create new property tables for the working fluid. If '1', new

tables are created; if '0', old tables are used. If tables are created, the input file `createtables.txt` must be used. An example `createtables.txt` input file contains the following input:

```

200      !...number of temperature points
200      !...number of pressure points
7000.0   !...table minimum pressure (kPa)
25000.0  !...table maximum pressure (kPa)
20.0     !...table minimum temperature (C)
650.0    !...table maximum temperature (C)

```

The above data, contained within the file `createtables.txt`, is only used if the table creation trigger is set to '1'.

Property trigger – The property trigger is an integer, either '1' or '0', that determines whether to use property tables or NIST 12 pure fluid property subroutines. If '1', subroutines are used; if '0', tables are used. The NIST 12 subroutines are more accurate, but take much longer to converge to a solution (on the order of hours). The tables are less accurate, but take much less time to converge to a solution (on the order of seconds).

Main compressor outlet pressure – This is both the pressure at the outlet of the main compressor as well as the maximum cycle pressure in kPa. The user should be cautious in changing this value because the pressure ratio of the main compressor should be changed in conjunction with it.

Cycle thermal power – The cycle thermal power, given in MWt, is the heat transfer rate into the cycle through the intermediate heat exchanger (IHX). The fixed cycle thermal power is used to calculate the mass flow rate by the formula:

$$\dot{m} = \frac{\dot{Q}_{in}}{\Delta h} \quad (3-9)$$

where \dot{Q}_{in} is the cycle thermal power (MWt), Δh is the enthalpy change across the IHX (kJ/kg), and \dot{m} is the mass flow rate (kg/s).

Pressure ratio of the main compressor – The pressure ratio of the main compressor is the ratio of the pressure at the outlet of the compressor to the pressure at the inlet of the compressor and is a dimensionless quantity:

$$r_{mcomp} = \frac{P_{out,mcomp}}{P_{in,mcomp}} \quad (3-10)$$

where r_{mcomp} is the pressure ratio of the main compressor, $P_{out,mcomp}$ is the pressure at the outlet of the main compressor (kPa), and $P_{in,mcomp}$ is the pressure at the inlet of the main compressor (kPa).

IHX outlet temperature – This is both the intermediate heat exchanger outlet temperature (°C) and the maximum cycle temperature.

Precooler outlet temperature – This is the precooler outlet temperature (°C) of the working fluid, CO₂.

Main compressor efficiency – The main compressor efficiency is the dimensionless quantity used to calculate the power required to run the main compressor by the formula:

$$\dot{W}_{mcomp} = \frac{\dot{m}_{mcomp} \cdot (h_{in} - h_{out,i})}{10^3 \cdot \eta_{mcomp}} \quad (3-11)$$

where \dot{W}_{mcomp} is the power required to run the main compressor (MW), \dot{m}_{mcomp} is the mass flow rate through the main compressor (kg/s), h_{in} is the specific enthalpy at the inlet of the main compressor (kJ/kg), $h_{out,i}$ is the ideal specific enthalpy at the outlet of the main compressor (kJ/kg), and η_{mcomp} is the main compressor efficiency (on a total-to-static basis).

Recompressing compressor efficiency – The recompressing compressor efficiency is the dimensionless quantity used to calculate the power required to run the recompressing compressor by a formula similar to that given in equation (3-11), except that each of the quantities refers to that of the recompressing compressor.

Turbine efficiency – The turbine efficiency is the dimensionless quantity used to calculate the power supplied by the turbine by the formula:

$$\dot{W}_{turb} = \frac{\eta_{turb} \cdot \dot{m}_{turb} \cdot (h_{in} - h_{out,i})}{10^3} \quad (3-12)$$

where \dot{W}_{turb} is the power supplied by the turbine (MW), \dot{m}_{turb} is the mass flow rate through the turbine (kg/s), h_{in} is the specific enthalpy at the inlet of the turbine (kJ/kg), $h_{out,i}$ is the specific enthalpy at the outlet of the turbine (kJ/kg), and η_{turb} is the turbine efficiency (on a total-to-static basis).

Mechanical efficiency (couplings) – The mechanical efficiency, which accounts for the friction and rubbing of the gears, affects the calculation of the net power of the system by the formula:

$$\dot{W}_{net} = (\dot{W}_{turb} \cdot \eta_{mech}) + \frac{\dot{W}_{mcomp}}{(\eta_{mech})^2} + \frac{\dot{W}_{recomp}}{\eta_{mech}} - \dot{W}_{pump} \quad (3-13)$$

where \dot{W}_{net} is the net power (MW), η_{mech} is the mechanical efficiency, and the power subscripts “turb”, “mcomp”, “recomp”, and “pump” refer to the turbine, main compressor, recompressing compressor, and pump, respectively.

Generator efficiency and frequency converter efficiency – These two efficiencies are combined to yield the electric efficiency. The generator efficiency accounts for how well mechanical power is converted into electrical power, and frequency converter efficiency accounts for how well AC is converted into (and/or from) DC. The electrical efficiency affects the calculation of the net cycle efficiency by the following calculations:

$$\eta_{net} = \eta_{elec} \frac{\dot{W}_{net}}{\dot{Q}_{in}} \quad (3-14)$$

$$\eta_{elec} = \eta_{gen} \cdot \eta_{fcon}$$

where η_{net} is the net efficiency, and the subscripts “elec”, “gen”, and “fcon” stand for electrical, generator, and frequency converter efficiency, respectively.

Cooling water inlet temperature – This is the inlet temperature of the cooling water in the precooler and the minimum cycle temperature in °C.

IHX pressure drop – The IHX (or reactor, for a direct cycle) pressure drop is the difference between the pressure at the inlet of the IHX and the pressure at the outlet of the IHX in kPa (a positive quantity):

$$dP_{IHX} = P_{in,IHX} - P_{out,IHX} \quad (3-15)$$

where dP_{IHX} is the IHX pressure drop (kPa), $P_{in,IHX}$ is the IHX inlet pressure (kPa), and $P_{out,IHX}$ is the IHX outlet pressure (kPa). The IHX is not modeled in CYCLES II, but input as a fixed pressure drop.

Tolerance – The tolerance is used to determine when to stop the convergence algorithm. A lower value ensures a more precise solution, while a higher value obtains a converged solution more quickly. At the end of the convergence loop, the fractional pressure drop of a component is compared to the tolerance. The fractional pressure drop of a component is calculated by the formula:

$$\text{Fractional pressure drop} = \frac{dP_n - dP_{n-1}}{dP_n} \quad (3-16)$$

where dP_n is the pressure drop of a particular component (LTR, HTR, or PRE) on the n^{th} convergence loop, and dP_{n-1} is the pressure drop of the same component on the previous convergence loop. As the convergence algorithm begins to reach a more accurate

solution, the value of the fractional pressure drop decreases. The convergence algorithm will exit when it reaches a value that is less than the tolerance. A typical value for the tolerance is 0.01.

HTR data

An example of the input within the HTR data section is

```

HTR data
htr          !...HX type
str1h1c     !...Channel type...
0.002       !...hot channel diameter (m)
0.002       !...cold channel diameter (m)
0.0015      !...hot plate thickness (m)
0.0015      !...cold plate thickness (m)
1.0         !...module height (m)
0.434783    !...module width (m)
2.3         !...module length (m)
66.86       !...heat exchanger volume (m3)
25.0        !...plate thermal conductivity (W/m-K)
40.0        !...number of axial nodes...
0.005       !...precision
100.0       !...initial step
1.3         !...initial step adjustment

```

Similar to the main cycle input data, for each line, the input parameter is given first, followed by a commented description. What follows is a more detailed description of each of the input parameters.

HX type – The heat exchanger type is a three character string that indicates the type of heat exchanger (‘htr’ for high-temperature recuperator, ‘ltr’ for low-temperature recuperator, and ‘pre’ for precooler).

Channel type – The channel type is a seven character string that indicates the type of channels used in the heat exchanger and the stacking pattern for the plates. If the first three letters are “str”, then the channels are straight; if the first three letters are “zig”, then the channels are of the zigzag type. The last four letters indicate the stacking pattern. The last four letters can either be “1h1c” a one-hot, one-cold alternating stacking pattern, “1h2c” for a one-hot, two-cold stacking pattern, or “2h1c” for a two-hot, one-cold stacking pattern.

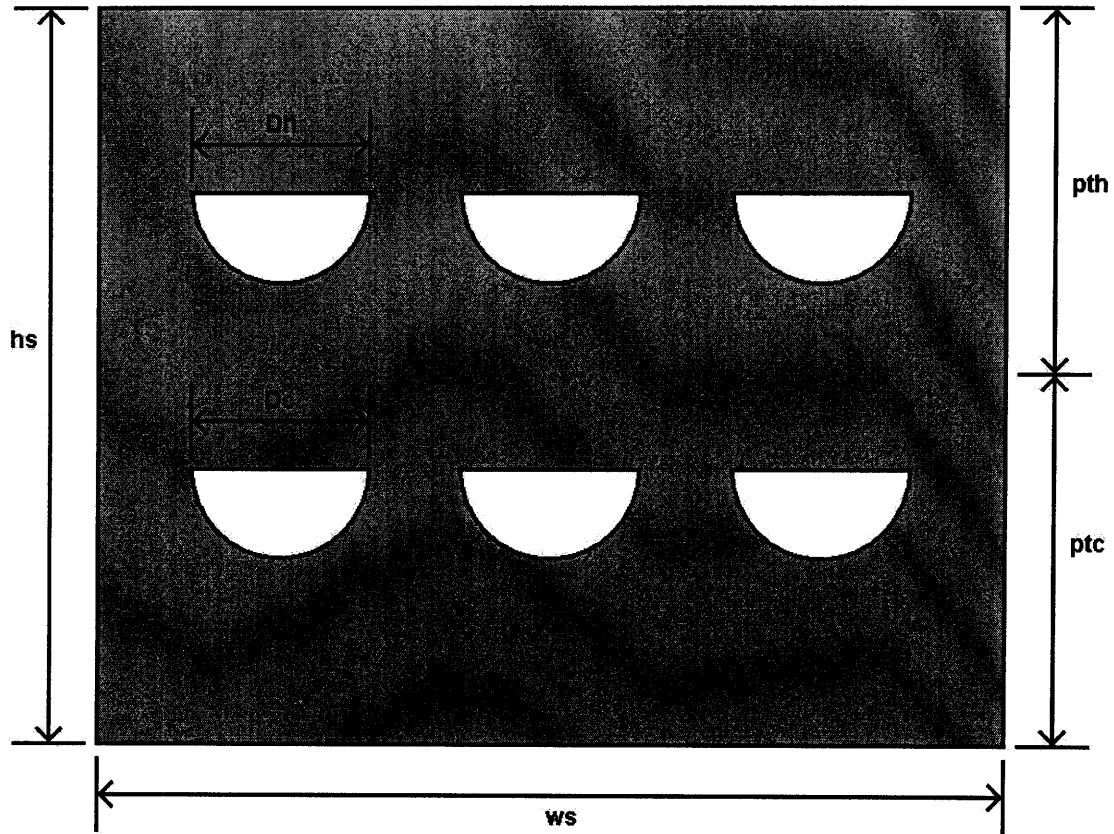


Figure 3.1: Heat exchanger profile

Hot channel diameter – This is the diameter D_h in meters of the semicircular-shaped hot channels shown in Figure 3.1.

Cold channel diameter – This is the diameter D_c in meters of the semicircular-shaped cold channels shown in Figure 3.1.

Hot plate thickness – This is the thickness pth in meters of the hot plates as shown in Figure 3.1.

Cold plate thickness – This is the thickness ptc in meters of the cold plates as shown in Figure 3.1.

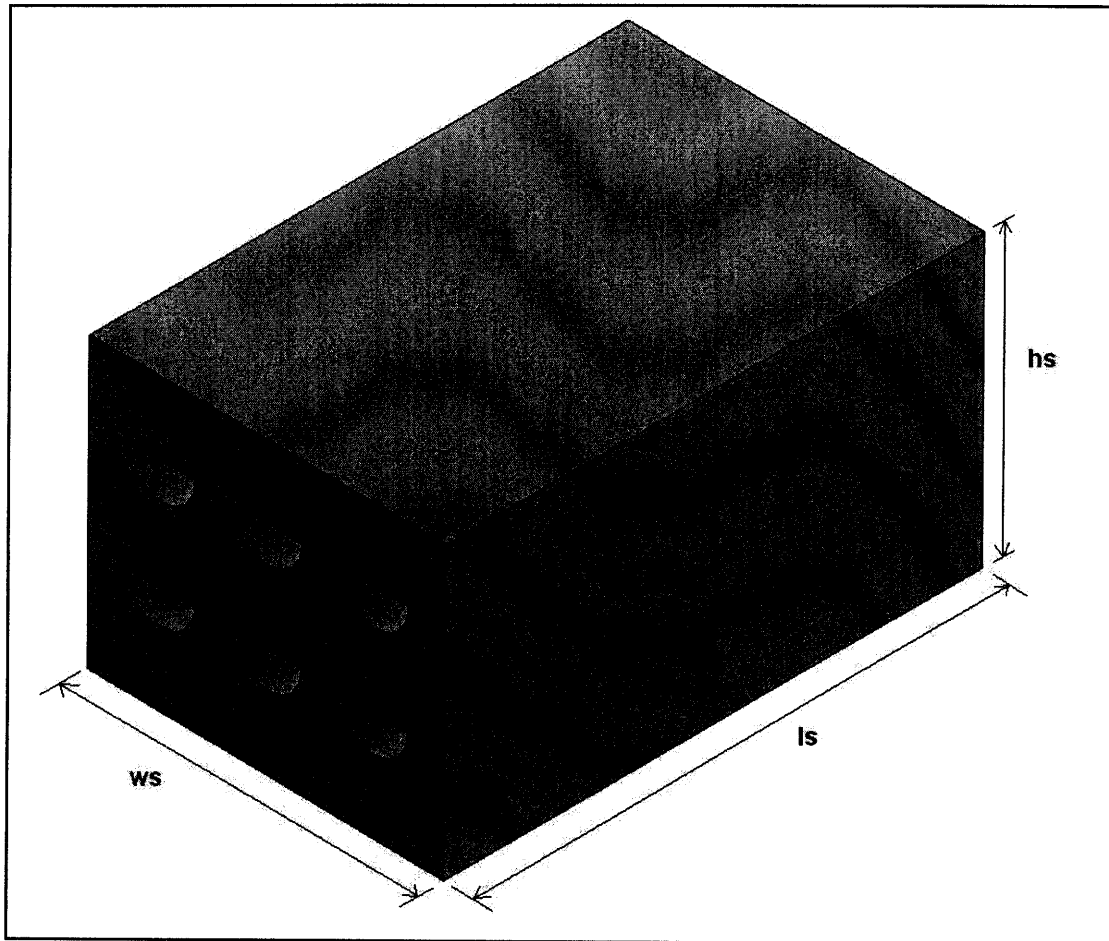


Figure 3.2: Dimensions of heat exchanger module

Module height – This is the height h_s in meters of one heat exchanger module as shown in both Figure 3.1 and Figure 3.2.

Module width – This is the width w_s in meters of one heat exchanger module as shown in both Figure 3.1 and Figure 3.2.

Module length – This is the length l_s in meters of one heat exchanger module as shown in Figure 3.1.

Heat exchanger volume – This is the total volume of the heat exchanger core in m^3 . Each module has a volume (length \times width \times height) of $1 m^3$, so the recuperator volume is also the total number of modules used in the calculation.

Plate thermal conductivity – This is the thermal conductivity of the plate in (W/m-K).

Number of axial nodes – This is the number of axial nodes used to calculate the thermal performance of the heat exchanger. The heat exchanger calculations use a convergence algorithm whereby the heat exchanger is broken up into many different axial nodes and the heat transfer is analyzed iteratively until a solution is converged.

Precision – This value is used in the convergence loop within the heat exchanger subroutines to determine how precise the calculations need to be before the convergence loop ends. A typical value is 0.005.

Initial step – This is the first value used as an increment to iterate a solution for the recuperator subroutine. A typical value for a 300 MW_e cycle is 100. This value needs to be scaled with power. Thus, for a 100 MW_e cycle, this value should be reduced to 0.333.

Initial step adjustment – This value is used to change the value of the incremental step each time convergence is not obtained. A typical value is 1.3 and is independent of power values.

LTR data

An example of the input within the LTR data section is

```
LTR data
htr          !...HX type
str1hc      !...Channel type...
0.002       !...hot channel diameter (m)
0.002       !...cold channel diameter (m)
0.0015      !...hot plate thickness (m)
0.0015      !...cold plate thickness (m)
1.0         !...module height (m)
0.5000      !...module width (m)
2.0         !...module length (m)
43.14       !...heat exchanger volume (m3)
25.0        !...plate thermal conductivity (W/m-K)
40.0        !...number of axial nodes...
0.005d0     !...precision
100.0d0     !...initial step
1.3d0       !...initial step adjustment
```

As shown, the input data for the low-temperature recuperator has the same number and type of parameters as the high-temperature recuperator. For a detailed description of each of the input parameters, refer to the previous section on “HTR data”.

PRE data

An example of the input within the PRE data section is

```
PRE data
pre          !...HX type
str1hc      !...Channel type...
0.002       !...hot channel diameter (m)
0.002       !...cold channel diameter (m)
0.0015      !...hot plate thickness (m)
```

```

0.0015      !...cold plate thickness (m)
1.0         !...module height (m)
1.11111111 !...module width (m)
0.90       !...module length (m)
10.0       !...heat exchanger volume (m3)
25.0       !...plate thermal conductivity (W/m-K)...
40         !...number of axial nodes...
0.0005d0   !...precision

```

As shown, the input data for the precooler has almost the same number and type of parameters as the data for both the high-temperature recuperator and the low-temperature recuperator. The only difference is that the precooler data lacks two parameters: initial step and initial step adjustment. For a detailed description of each of the input parameters, refer to the previous section on “HTR data”.

Pipe and plena data

The pipe data includes the information about the geometry and physical characteristics of the pipes, as well as that for the various plena. An abbreviated example of the input within the Pipe data section is given in Figure 3.3. The data is divided up into pipe paths, (labeled “precooler to main compressor”, “main compressor to LTR”, etc.) where each pipe path is numbered in the cycle schematic in Figure 2.1. The pipe paths contain different sections, where each section is made up of one or more identical pipes or plena. When multiple pipes or plena are given in a section, it indicates that they are parallel. A description of each of the sections within the pipe paths is provided as a comment in the right-most column. The data is sorted into columns, and the titles of the columns indicate the variable type.

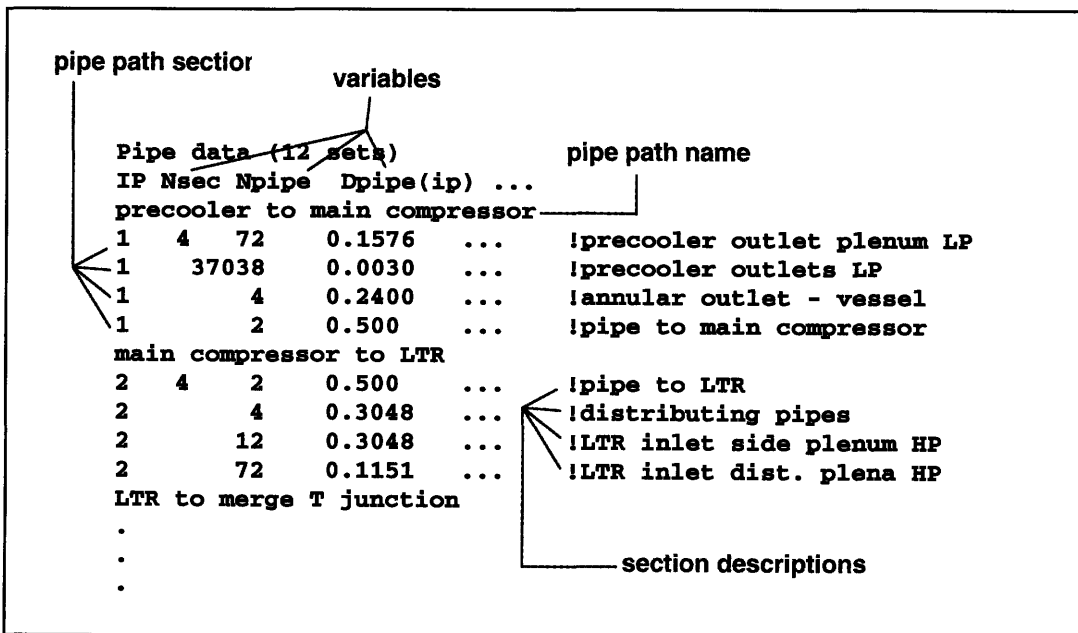


Figure 3.3: Description of “Pipe data” section of input file HXdata.txt

A description of the variables used to store the data in the pipe data section is given in Table 3.1.

Table 3.1: Description of variables used in the “Pipe data” section of HXdata.txt

Variables	Description
ip	pipe path number
NSec(ip)	number of pipe sections with different flow areas (in series) for each path ip
Npipe(j, ip)	number of parallel passages in section j of path ip
Dpipe(j, ip)	hydraulic diameter for section j of path ip (m)
Apipe(j, ip)	cross sectional area for section j of path ip (m ²)
ELpipe(j, ip)	pipe length for section j of path ip (m)
xsi_pipe(j, ip)	form loss coefficient for section j of path ip (dimensionless)
rough_pipe(j, ip)	pipe roughness for section j of path ip (m)

The pipe layout scheme given in Figure 2.1 can be misleading, since a pipe path can include multiple pipes and plena. For example, for the pipe path from the turbine to the HTR, it could consist of two turbine exhaust pipes in parallel, followed by distributing pipes, then thousands of inlet channels, and finally, fifty or more inlet plena that lead into the passages of the HTR core. To understand the basics of the pipe and plena input data in the input file, a simplified example is given in Figure 3.4 that shows a pipe path that runs from the turbine to two high-temperature recuperators.¹

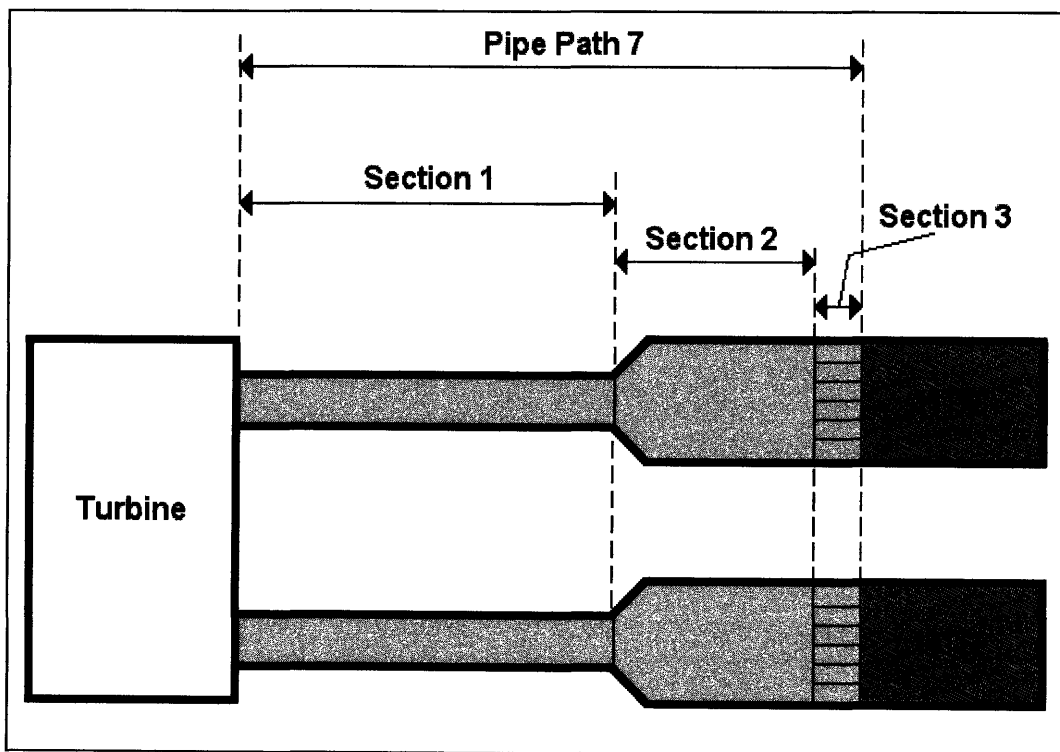


Figure 3.4: Pipe and plena input example

¹ Note: this example is not indicative of a real system. The layout and pipe sizes are arbitrary.

The pipe path is divided into three sections: section 1 contains two pipes in parallel, each with a diameter 0.3 m, section 2 contains two distribution pipes of 0.6 m, and section 3 contains two sets of 6 plena, each with a diameter of 0.1 m, that lead to the HTR core. The input data given in the input file for pipe path 7 is given in Figure 3.5.

Pipe data							
IP	Nsec	Npipe	Dpipe (ip) (m)	Apipe (ip) (m ²)	ELpipe (ip) (m)	xsi_pipe (ip)	rough_pipe (m)
turbine to HTR							
7	3	2	0.3	0.07069	2.00	0.60	1.0E-04
7		2	0.6	0.28274	1.00	1.90	1.0E-04
7		12	0.1	0.00785	0.15	1.20	1.0E-04
.							
.							
.							

Figure 3.5: Pipe and plena input data example

The pipe path name is “turbine to HTR”, and the pipe path number (ip) is 7, as shown for each of the sections in the left-most column of numbers. The second column contains one number which indicates the number of sections (Nsec). The third column gives the diameter of each of the pipes or plena in the pipe paths sections. Notice that in the third section, the total number of plena equals 12 and not 6, since all plena in parallel are counted. For non-circular pipes, this value would be a hydraulic diameter. The cross sectional area is listed in the fourth column. For this example, the pipes were made circular, so the cross sectional area is simply $D^2\pi/4$. The length of the sections is given under “ELpipe”. The values “xsi_pipe” and “rough_pipe” are simply the form loss coefficients and roughness for each section.

3.3 Output

The output data for the program is written in the file `output.txt`, which contains data for heat exchangers, turbomachinery, pipes, and the overall cycle. Also included is a cycle schematic for reference. This section describes the output file and all its parameters.

The `output.txt` file is broken up into five sections: “Cycle schematic”, “Heat exchangers”, “Further heat exchanger data”, “Turbomachinery”, “Pipes”, and “Overall cycle”. An example of all the data contained in the output file is given in Figure 2.4.

Cycle Schematic

This section provides a simple cycle schematic with all the components and pipe path numbers. The arrows along the pipe paths are provided to show the direction of mass flow. The connection between the main compressor, recompressing compressor, and the turbine represents the shaft. Descriptions of the pipe path numbers are given next to the schematic. A list of the terms used in this section and a description for each is given in Table 3.2.

Table 3.2: Description of terms used in the “Cycle Schematic” section of output.txt

Terms	Description
HTR	high-temperature recuperator
LTR	low-temperature recuperator
PRE	precooler
MCOMP	main compressor
RECOMP	recompressing compressor
TURB	turbine
IHX	intermediate heat exchanger
merge junction	intersection of pipes 3, 4, and 12
split junction	intersection of pipes 9, 10, and 11

Heat Exchangers

This section provides important cycle state point parameters for the high-temperature recuperator, low-temperature recuperator, and precooler. Hot and cold side parameters are shown for each heat exchanger. A list of the terms used in this section and a description of each is given in Table 3.3. All values refer to the *active length* or *core* of the heat exchangers, which do NOT include the plena.

Table 3.3: Description of terms used in the “Heat Exchangers” section of output.txt

Terms	Description
HTR hot	hot side of high-temperature recuperator
HTR cold	cold side of high-temperature recuperator
LTR hot	hot side of low-temperature recuperator
LTR cold	cold side of low-temperature recuperator
PRE CO2	CO ₂ side of precooler
PRE H2O	cooling water side of PRE
Tin (C)	inlet temperature in °C
Tout (C)	outlet temperature in °C
Pin (kPa)	inlet pressure in kPa
Pout (kPa)	outlet pressure in kPa
dP (kPa)	inlet pressure minus outlet pressure in kPa
Q (MWt)	heat transfer rate in MWt (positive is heat in, negative is heat out)
mdot (kg/s)	mass flow rate in kg/s
vout (m/s)	outlet velocity in m/s
Re	Reynolds number (dimensionless quantity)

The heat transfer rate for each stream in the heat exchangers is calculated as follows:

$$\dot{Q}_{stream} = \dot{m} \cdot (h_{out} - h_{in}) \cdot 10^{-3} \quad (3-17)$$

where \dot{Q}_{stream} is the heat transfer rate (MWt) for either the hot or cold stream, \dot{m} is the mass flow rate (kg/s) for that stream, and h_{out} and h_{in} are the outlet and inlet specific enthalpies (kJ/kg) for that stream, respectively. The mass flow rate of each stream is determined by the total mass flow rate of the system and, for the LTR, the fraction of the flow rate that splits to the main compressor. The outlet velocity of each stream in the heat exchangers is calculated as follows:

$$v_{out,stream} = \frac{\dot{m}_{passage}}{\rho \cdot A_{passage}} \quad (3-18)$$

where $v_{out,stream}$ is the outlet velocity (kg/s) for either the hot or cold stream, $\dot{m}_{passage}$ is the mass flow rate of the fluid per passage for that stream, ρ is the density of the fluid (kg/m³) at the outlet for that stream, and $A_{passage}$ is the passage cross sectional area (m²). The Reynolds number of each stream in the heat exchangers is calculated as follows:

$$Re_{stream} = \frac{d_h \cdot \dot{m}_{passage}}{\mu \cdot A_{passage}} \quad (3-19)$$

where Re_{stream} is the Reynold's number (dimensionless) for either the hot or cold stream, d_h is the hydraulic diameter of a passage (m), and μ is the viscosity of the fluid (Pa-s).

Further Heat Exchanger Data

This section provides the overall heat transfer coefficient and effectiveness for each heat exchanger, as well as the module dimensions and the number of hot and cold channels. All parameters refer to the heat exchangers as a whole. A list of the terms used in this section and a description of each is given in Table 3.4.

Table 3.4: Description of terms used in the “Further Heat Exchanger Data” section

Terms	Description
HTR	high-temperature recuperator
LTR	low-temperature recuperator
PRE	precooler
U (W/m²-K)	overall heat transfer coefficient in W/(m ² -K)
eff	effectiveness
Mod Height (m)	module height in meters
Mod Width (m)	module width in meters
Mod Length (m)	module length in meters
Core Vol (m³)	core volume in m ³
Passages H	total number of hot passages
Passages C	total number of cold passages

All values refer to the *active length* or *core* of the heat exchangers, which do NOT include the plena. The overall heat transfer coefficient is calculated as follows:

$$U = \frac{1}{\frac{1}{h_h} + \frac{t}{k} + \frac{1}{h_c}} \quad (3-20)$$

where U is the overall heat transfer coefficient ($\text{W/m}^2\text{-K}$), h_h and h_c are the heat transfer coefficients ($\text{W/m}^2\text{-K}$) of the hot and cold streams, respectively, t is the conductance length (m), and k is the thermal conductivity (W/m-K). The effectiveness of the heat exchanger is the ratio of the actual heat transfer rate to the ideal heat transfer rate and is calculated as follows:

$$\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{ideal}} = \frac{h_{in,hot} - h_{out,hot}}{h_{in,hot} - h_{idealout,hot}} \quad (3-21)$$

where ε is effectiveness (dimensionless), \dot{Q} is heat transfer rate (W), and h is specific enthalpy (kJ/kg). The subscripts “in” and “out” represent the inlet and outlet of the heat exchanger, and the subscript “hot” stands for hot stream. The total number of passages for both the cold and hot streams of the heat exchangers is calculated within the “PCHEvol” subroutine and is based on the geometry. To determine the total number of passages for each stream, the number of passages per plate is multiplied by the number of plates and the HX volume.

Turbomachinery

This section provides cycle state point parameters for the main compressor, recompressing compressor, and the turbine. A list of the terms used in this section and a description of each is given in Table 3.5.

Table 3.5: Description of terms used in the “Turbomachinery” section of output.txt

Terms	Description
MCOMP	main compressor
RECOMP	recompressing compressor
TURB	turbine
Tin (C)	inlet temperature in °C
Tout (C)	outlet temperature in °C
Pin (kPa)	inlet pressure in kPa
Pout (kPa)	outlet pressure in kPa
dP (kPa)	inlet pressure minus outlet pressure in kPa
W (MW)	power in MW (positive is work out, negative is work in)
mdot (kg/s)	mass flow rate in kg/s
eta	turbomachinery efficiency (dimensionless quantity)
Pratio	outlet pressure over inlet pressure (dimensionless quantity)

Pipes

This section provides important cycle state points for each of the pipes. Parameters include inlet and outlet temperatures and pressures, pressure drops, and outlet velocities. A list of the terms used in this section and a description of each is given in Table 3.6.

Table 3.6: Description of terms used in the “Pipes” section of output.txt

Terms	Description
Pipe No. (1-12)	pipe path number between 1 and 12, as given in the cycle schematic
T_{in} (C)	inlet temperature in °C
T_{out} (C)	outlet temperature in °C
P_{in} (kPa)	inlet pressure in kPa
P_{out} (kPa)	outlet pressure in kPa
dP (kPa)	inlet pressure minus outlet pressure in kPa
v_{out} (m/s)	outlet velocity in m/s

Overall Cycle

This section provides data for the overall cycle. Parameters include efficiencies, heat transfer rate in, heat transfer rate out, net power, pump power, minimum temperature difference in the heat exchangers, reactor pressure drop, and fractional flow rate to the main compressor. A list of the terms used in this section and a description of each is given in Table 3.7.

Table 3.7: Description of terms used in the “Overall Cycle” section of output.txt

Terms	Description
eta1	efficiency of cycle calculated using equation (3-22) (dimensionless quantity)
eta2	efficiency of cycle calculated using equation (3-23) (dimensionless quantity)
eta-net	efficiency of the cycle reduced by the power required to pump water through the precooler calculated using equation (3-14) (dimensionless quantity)
Q_{in} (MWt)	heat transfer rate into the cycle in MWt
Q_{out} (MWt)	heat transfer rate out of the cycle in MWt
W_{net} (MW)	total power of the turbomachinery in MW does not include pump power
W_{pump} (MW)	pumping power of water through the precooler in MW
dT_{min} (C)	the minimum temperature difference in heat exchangers, 0 is for positive temperature difference in all heat exchangers
dP_{IHX} (kPa)	pressure drop in the intermediate heat exchanger in kPa
Main Comp Flow Frac	fraction of mass flow that diverts to the main compressor at the split junction in the cycle schematic (dimensionless quantity)

Three different efficiencies are given in this section of the output. The first two efficiencies, eta1 and eta2, are the cycle efficiencies calculated without factoring in the pumping power of water through the precooler. They are used as a measure of the accuracy of the convergence algorithm. The formula used to calculate eta1 is:

$$\eta_1 = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} \quad (3-22)$$

where η_1 is the first calculation of cycle efficiency (dimensionless), \dot{Q}_{in} is the heat transfer rate into the cycle (MWt), and \dot{Q}_{out} is the heat transfer rate out of the cycle (MWt). The formula used to calculate eta2 is:

$$\eta_2 = \frac{\dot{W}_t + \dot{W}_{mc} + \dot{W}_{rc}}{\dot{Q}_{in}} \quad (3-23)$$

where η_2 is the second calculation of cycle efficiency (dimensionless), \dot{W}_t is the power of the turbine (MW) (a positive quantity), \dot{W}_{mc} is the power of the main compressor (MW) (a negative quantity), and \dot{W}_{rc} is the power of the recompressing compressor (MW) (a negative quantity). The quantities η_1 and η_2 should be almost the same value, but this depends on the value of the tolerance given in the input file `HXdata.txt`. A typical value for the tolerance is 0.01. If the two quantities are not close to the same value, then the tolerance should be reduced. The two efficiencies may not reach an equivalent value, even at very low tolerances. The third value for cycle efficiency, eta-net, factors in the power required to pump water through the precooler, as well as mechanical and electrical efficiencies to provide a more accurate value of the cycle efficiency. The formula used to calculate eta-net is given in equation 3-14.

3.4 *CYCLES II algorithm overview*

The algorithm logic for CYCLES II is represented in the flow chart in Figure 3.6. The flow chart lists the sequence of subroutine calls within the code. Not all the subroutine calls are listed, but the ones that are provide a clear enough understanding of the logic. For each subroutine call, the input and output parameters that are passed within the subroutine call are given. All other parameters that are used globally in the program are shown in the box “Global Parameters.”

When the program first executes, the input files are read by calling the subroutine “ReadHX”. In this subroutine, the data from the property files and the file `HXdata.txt` are input into the program. If tables are set to be created, this is performed within the subroutine “ReadHX” too.

The convergence algorithm begins after reading the input files. The thermodynamics of the different cycle components (heat exchangers, turbomachinery, and pipes) is calculated by calling a separate subroutine. The turbomachinery subroutines are called first, followed by the heat exchangers. The pipe subroutine calls are interspersed throughout the convergence loop. Before the LTR subroutine is called, the fractional flow split is recalculated by the following formula:

$$\text{Fraction of flow to main compressor} = \frac{h_{out,HTRhot} - h_{out,LTRhot}}{h_{out,pipe4} - h_{out,pipe2}} \quad (3-24)$$

where h is specific enthalpy (kJ/kg), and the subscripts refer to the outlets of the hot streams of the HTR and LTR, and the outlets of pipe 4 and pipe 2. At the end of each loop in the convergence algorithm, the code checks to see if the fractional pressure drops across each of the components from the previous loop lies within a specified tolerance, as shown in equation 3-16. If not, a new mass flow rate is calculated and the convergence algorithm loops until the pressure drops are less than the tolerance value. The formula used to calculate the new mass flow rate is:

$$\dot{m} = \frac{\text{Power}}{\Delta h_{IHX}} \quad (3-25)$$

where \dot{m} “Power” is the cycle thermal power (kW), and Δh_{IHX} is the change in enthalpy across the IHX (kJ/kg). Once convergence is reached, the calculations are printed by calling the function “Output” and then the program ends.

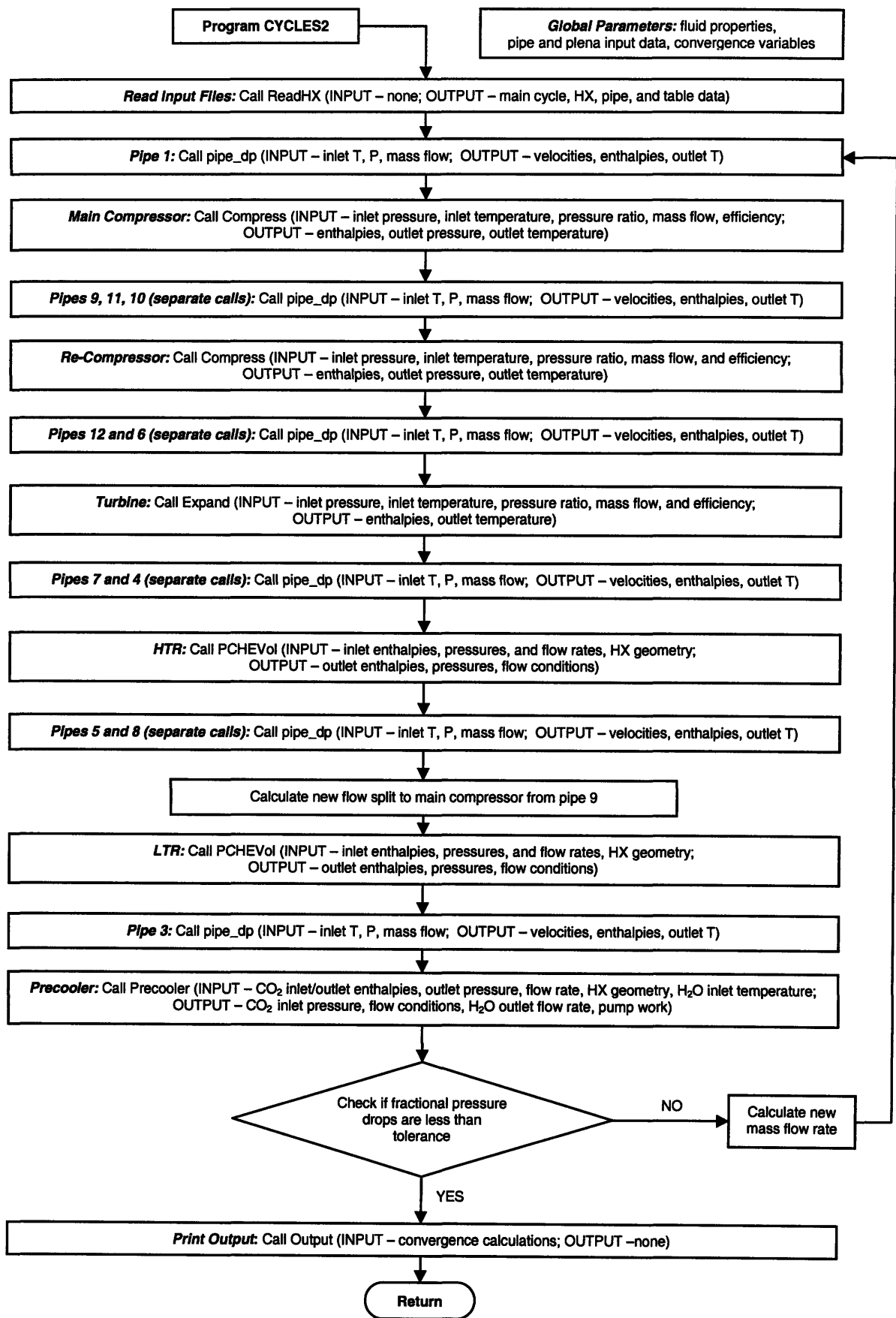


Figure 3.6: CYCLES II algorithm flow chart

3.5 Reproducing results of *CYCLES* using *CYCLES II*²

To compare the results of the two versions of the code, the input of *CYCLES II* was set to have zero pressure drops across the pipes and plena. This was done by setting the length of the pipes and plena equal to zero and the form loss coefficients equal to zero. Other than the pipe input data for *CYCLES II*, the rest of the input was identical. That is, the main cycle input, turbomachinery input, and heat exchanger input were equal for *CYCLES* and *CYCLES II*. The results of the two runs are given in Figure 3.7 and Figure 3.8.

As seen in the two figures, the absolute input and output temperatures for the heat exchangers and the turbomachinery calculated using *CYCLES* are within 0.1% of those same temperatures calculated using *CYCLES II*. The inlet and outlet pressures for the heat exchangers and turbomachinery are equivalent to one-tenth of a kPa. As for the overall cycle, the three versions of efficiency, η_{a1} , η_{a2} , and η_{net} are essentially the same under both versions of the code. Additionally, the heat transfer in and out, and the power out are all within 0.1% of the same value for *CYCLES* and *CYCLES II*.

² The input and output files used in this application are included in the electronic version of the thesis on CD under the path "Applications\Job 0"

=====CYCLES OUTPUT=====

HEAT EXCHANGERS

	Tin (C)	Tout (C)	Pin (kPa)	Pout (kPa)	dP (kPa)	Q (MWt)	mdot (kg/s)
HTR hot	528.32	185.88	7692.7	7692.6	0.150	-73.8	187.3
HTR cold	168.04	477.64	20000.0	19999.9	0.055	73.8	187.3
LTR hot	185.88	77.34	7692.6	7692.5	0.081	-25.1	187.3
LTR cold	61.10	167.96	20000.0	20000.0	0.021	0.0	112.0
PRE CO2	77.34	32.00	7692.5	7692.3	0.208	-20.6	112.0
PRE H2O	20.00	38.26					270.1

TURBOMACHINERY

	Tin (C)	Tout (C)	Pin (kPa)	Pout (kPa)	dP (kPa)	W (MWt)	mdot (kg/s)
MCOMP	32.00	61.10	7692.3	20000.0	-12307.7	-2.3	112.0
RECOMP	77.28	168.04	7692.5	20000.0	-12307.5	-4.6	75.3
TURB	650.00	528.32	19499.9	7692.7	11807.2	26.5	187.3

PIPES NOT MODELED

OVERALL CYCLE

eta1	eta2	eta-net	Q in (MWt)	Q out (MWt)	W net (MW)	W pump (kW)	dT min (C)
0.49	0.49	0.47	40.19	20.61	19.23	-0.62	0.00

Figure 3.7: CYCLES Output—reproducing the results of CYCLES using CYCLES II

=====CYCLES II OUTPUT=====

HEAT EXCHANGERS

	Tin (C)	Tout (C)	Pin (kPa)	Pout (kPa)	dP (kPa)	Q (MWt)	mdot (kg/s)
HTR hot	528.32	185.48	7692.7	7692.6	0.150	-73.9	187.4
HTR cold	167.66	477.55	20000.0	19999.9	0.053	73.9	187.4
LTR hot	185.48	77.32	7692.6	7692.5	0.081	-25.0	187.4
LTR cold	61.10	167.49	20000.0	20000.0	0.021	25.0	112.0
PRE CO2	77.22	32.00	7692.5	7692.3	0.209	-20.6	112.0
PRE H2O	20.00	38.22					270.4

TURBOMACHINERY

	Tin (C)	Tout (C)	Pin (kPa)	Pout (kPa)	dP (kPa)	W (MWt)	mdot (kg/s)
MCOMP	32.00	61.10	7692.3	20000.0	-12307.7	-2.3	112.0
RECOMP	77.03	167.72	7692.5	20000.0	-12307.5	-4.6	75.4
TURB	650.00	528.32	19499.9	7692.7	11807.2	26.5	187.4

PIPES

Pipe No.	Tin (C)	Tout (C)	Pin (kPa)	Pout (kPa)	dP (kPa)	vout (m/s)
1	32.00	32.00	7692.3	7692.3	0.0	0.5
2	61.10	61.10	20000.0	20000.0	0.0	0.2
3	167.49	167.49	20000.0	20000.0	0.0	1.0
4	167.66	167.66	20000.0	20000.0	0.0	0.8
5	477.55	477.55	19999.9	19999.9	0.0	2.4
6	650.00	650.00	19499.9	19499.9	0.0	3.1
7	528.32	528.32	7692.7	7692.7	0.0	1.1
8	185.48	185.48	7692.6	7692.6	0.0	0.7
9	77.22	77.22	7692.5	7692.5	0.0	1.2
10	77.22	77.22	7692.5	7692.5	0.0	0.5
11	77.22	77.22	7692.5	7692.5	0.0	0.9
12	167.72	167.73	20000.0	20000.0	0.0	0.9

OVERALL CYCLE

eta1	eta2	eta-net	Q in (MWt)	Q out (MWt)	W net (MW)	W pump (kW)	dT min (C)
0.49	0.49	0.47	40.23	20.60	19.25	-0.62	0.00

Figure 3.8: CYCLES II Output—reproducing the results of CYCLES using CYCLES II

3.6 Chapter summary

The purpose of this chapter was to provide a basic understanding of the CYCLES II algorithms and also to provide a detailed description of the input and output files used in the program. The description of the input file `HXdata.txt` is subdivided according to the five sections included in the file: main cycle input data, HTR data, LTR data, PRE data, and pipe data. Likewise, the description of the output file `output.txt` is subdivided into the following sections: cycle schematic, heat exchangers, further heat exchanger data, turbomachinery, pipes, and overall cycle. In addition to the detailed descriptions of the files contained within this chapter, the files themselves are adequately commented to provide enough information without having to reference this chapter. The flow chart at the end of the chapter provides a picture of the algorithm logic used by the program. In the last section of the chapter, CYCLES II was run with zero pressure drops across the pipes and plena to show that the code can reproduce the same results as CYCLES.

4 CYCLES II APPLICATIONS

4.1 Effect of pressure drops on cycle performance³

As mentioned in section 2.2, an important change made in CYCLES II was the calculation of pressure drops in piping and HX plena. The original code, CYCLES, did not account for these losses. To determine the effect of pressure drops on cycle performance, a comparison was made between the MIT version of a 300 MW_e, dispersed layout, supercritical CO₂ Brayton PCS, having turbine inlet conditions of 650°C and 18.7 MPa with and without pipes and plena connecting heat exchangers and turbomachinery. To model zero pressure drops across the pipes and the plena, the lengths and form loss coefficients were set equal to zero. This is the same procedure that was used in section 3.5 when CYCLES and CYCLES II calculations were compared.

In the first run, all pipe and plena pressure drops were set equal to zero. In the second run, the pressure drops due to the high-pressure pipes were added, followed by the pressure drops due to the high-pressure plena.⁴ The next run included pressure drops due to low-pressure pipes, and the last run included pressure drops due to the low-pressure plena. Except for the pipe and plena input data, all other parameters were kept constant for each run. The pipe and plena input data for each run are given in Appendix 6.2: Job 1 Input. Note that the diameters specified ranged from 0.6 to 0.8 m—at the upper limit of typical large power station values. A summary description of the input for each run, and the calculated net cycle efficiency is given in Table 4.1.

Table 4.1: Summary input and net efficiency for each run, Job 1

Run	Input Summary	eta-net
1	Pipe and plena pressure drops set equal to zero	0.49
2	HP pipe pressure drops included	0.48
3	HP pipe and plena pressure drops included	0.47
4	HP pipe, HP plena, and LP pipe pressure drops included	0.45
5	All pipe and plena pressure drops included	0.45

The calculations show that the net cycle efficiency drops 4% when the pressure drops due to the pipes and plena are considered. The largest efficiency drop occurs when the LP pipe pressure drops are included in run 4. The losses are therefore largest in the LP pipes. The smallest efficiency drop occurs when the pressure drops of the LP plena are added and the calculated efficiency remains the same. This is because the LP plena were designed such that their pressure drop is minimized. This is necessary since cycle efficiency is very sensitive to pressure drops of the lower pressure side.

³ The input and output files used in this application are included in the electronic version of the thesis on CD under the path "Applications\Job 1"

⁴ The high pressure pipe paths are defined as the pipes through which the working fluid flows after the compressors but before the turbine (numbered 2, 3, 4, 5, 6, and 12 in Figure 2.1). The low pressure pipe paths are all the other pipes, which are defined as the pipes through which the working fluid flows after the turbine but before the compressors (numbered 1, 7, 8, 9, 10, and 11 in Figure 2.1).

4.2 Effect of pipe dimensions on cycle performance⁵

This application shows that the dimensions of the pipes can have a substantial impact on cycle performance. CYCLES II was run once using normal values for pipe dimensions. The program was then run four more times with one or more varying pipe diameters in each run. The pipe and plena input data for each run are given in Appendix 6.2: Job 2 Input. A summary description of the input for each run, and the calculated net cycle efficiency is given in Table 4.2. Please refer to Figure 2.1 for the pipe numbering scheme.

Table 4.2: Summary input and net efficiency for each run, Job 2

Run	Input Summary	eta-net
1	All pipe and plena pressure drops included, pipe sizes normal	0.45
2	Pipe 7 diameter changes from 0.8 m to 0.6 m (a low pressure pipe), other pipes normal sizes	0.43
3	Pipe 5 diameter changes from 0.6 m to 0.5 m (a high pressure pipe), other pipes normal sizes	0.45
4	Pipes 7, 8, 9 shrink by $\sqrt{2}$ (low pressure pipes), other pipes normal sizes	0.36
5	Pipes 2, 3, 4, 5, 6, 12 diameters shrink by $\sqrt{2}$ (high pressure pipes), other pipes normal sizes	0.42

In the first run, all pipe sizes are normal, and the net total efficiency is 0.45. In the second run, only the diameter of pipe 7 was reduced, and the efficiency dropped 2%. The results of run 2 show that a seemingly reasonable reduction in the diameter of a low pressure pipe can have a significant impact on cycle performance. On the other hand, when the pipe diameter of one of the pipes in the high pressure region was reduced in run 3, the efficiency was unaffected. In run 4, three LP pipes were reduced in diameter by a factor of $\sqrt{2}$ and the net-cycle efficiency suffered a 9% loss. In run 5, a total of seven HP pipes were reduced in diameter by a factor of $\sqrt{2}$, but the cycle efficiency only decreased by 3%. The results clearly indicate the importance of pipe size on cycle efficiency. The LP pipe effects are more sensitive to changes in pipe diameter and have a greater effect on cycle efficiency than the HP pipes.

4.3 Chapter summary

The purpose of this chapter was to provide applications of the code to demonstrate its functionality and also to show the effect of the pipe and plena pressure drops on cycle performance. In the first application, the program was first run with zero pipe losses, and in the following runs, different sets of pipe and plena pressure drops were included in the calculation. The calculations showed how the HP and LP pipe and plena groups affected cycle efficiency. When all pipe and plena pressure drops were included, the cycle

⁵ The input and output files used in this application are included in the electronic version of the thesis on CD under the path "Applications\Job 2"

efficiency dropped by 4% compared to the case with no pipe and plena pressure drops. In the second application, all runs were modeled with pipe and pressure drops included, but one or more pipe diameters varied for each successive run. The results indicate that changes in the dimensions of LP pipes have a much greater effect on cycle performance than changes in dimensions of the HP pipes. Also, what may seem like a reasonable change in pipe size for even one LP pipe can reduce cycle efficiency by 2%. The effect that pipes have on cycle efficiency is not specific to the S-CO₂ cycle. All Brayton cycles have this issue, which is due to the low c_p values and high gas velocities of the working fluid. In fact, the pipe effects in the helium-Brayton cycle are worse because of lower operating pressures.

5 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The advantages posed by the S-CO₂ power conversion system have opened up doors to many different areas of research. Similar to the most developed closed gas-turbine cycle (helium-Brayton), the S-CO₂ cycle is able to achieve efficiencies of over 40%, but at much lower temperatures. Also, due to the properties of CO₂ close to the critical point, the cycle is able to operate at high power densities, which leads to a reduction in the size of turbomachinery.

Given the heightened interest in research on S-CO₂ cycles, it is essential that sound software be developed to analyze the cycle thermodynamics. The strides that have already been made need to be documented so that those who follow can learn what their predecessors have accomplished. The CYCLES II code, modified from the original code developed by Vaclav Dostal, has great potential for any who desire to do research on the S-CO₂ recompression cycle. The modifications have made the code more accurate and easier to use for researchers unfamiliar with the code. In particular, pressure drops in pipes and plena have been incorporated. This report provides a summary of all the changes made to CYCLES and a documentation of the code so that others will be able to utilize it.

Though much has been done to the code, more enhancements can still be made. Some areas of further research and development, with respect to the CYCLES II code, include the following:

1. The code needs to have more consistency checks and error flags to prevent the user from supplying bad input data.
2. Though much of the code is written in FORTRAN90 formatting, some of the subroutines are written with the formatting of FORTRAN77. The code should be changed to have uniform formatting throughout.
3. Much work has gone into commenting the program and all its subroutines, though this task is not yet complete.
4. The program could provide a plot of the states on a T-s or a P-V diagram, given the input conditions.
5. The code should be run against other S-CO₂ cycle codes to verify the accuracy of the calculations.
6. A bypass capability should be added to the cycle layout in the code to permit simulation of part load operation.
7. The IHX (or reactor, for a direct cycle) should be modeled in more detail.

6 APPENDIX

6.1 *Listing of files on CD*

The following files are contained on the CD, available with the report version of this thesis: "CYCLES II: A Steady State Code for Supercritical CO₂ Power Conversion System Calculations" (MIT-GFR-036).

1. Copy of thesis as an MS Word document
2. Folder of figures used in thesis
3. CYCLES II program and files
4. CYCLES I program and files
5. Application section input and output files

6.2 *Job 1 input*

Figures 6.1 through 6.5 show the pipe input data for Job 1.

6.3 *Job 2 input*

Figures 6.6 through 6.10 show the pipe input data for Job 2.

6.4 Nomenclature

Table 6.1 and Table 6.2 list abbreviations and symbols used throughout the report. Notice that the units for both CYCLES and CYCLES II are the same except for temperature.

Table 6.1: Description of quantities used in this report

Quantity	Symbol	Units: CYCLES	Units: CYCLES II
Effectiveness	eff, ϵ	(dimensionless)	(dimensionless)
Efficiency	eta, η	(dimensionless)	(dimensionless)
Heat transfer rate	\dot{Q}	MW	MW
Heat transfer coefficient (hot/cold)	h_p, h_c	W/m ² -K	W/m ² -K
Heat transfer coefficient (overall)	U	W/m ² -K	W/m ² -K
Length	various ones used	m	m
Mass flow	mdot, \dot{m}	kg/s	kg/s
Power	\dot{W}	MW	MW
Pressure	P	kPa	kPa
Pressure drop	dP	kPa	kPa
Pressure ratio	Pratio, r	(dimensionless)	(dimensionless)
Reynolds number	Re	(dimensionless)	(dimensionless)
Specific enthalpy	h	kJ/kg	kJ/kg
Specific entropy	s	kJ/kg-K	kJ/kg-K
Temperature	T	°C	K
Thermal conductivity	k	W/m-K	W/m-K
Velocity	v	m/s	m/s

Table 6.2: Description of abbreviations used in this report

Abbreviation	Definition
S-CO ₂	supercritical carbon-dioxide
htr, HTR	high-temperature recuperator
ltr, LTR	low-temperature recuperator
pre, PRE	precooler
mcomp, MCOMP	main compressor
recomp, RECOMP	recompressing compressor
turb, TURB	turbine
IHX	intermediate heat exchanger
LP	low power
HP	high power
Mod	module
in/out (subscripts)	inlet/outlet, or “in to system”/“out of system” when used with a heat transfer rate
t/e (subscripts)	used with MW, refers to MW “thermal” or MW “electric”
PCS	Power Conversion System

====CYCLES II INPUT: Job 1 Run 1====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0	0	1.0E-04
1	37038		0.0030	0.000090	0	0	1.0E-04
1	4		0.2400	0.360000	0	0	1.0E-04
1	2		0.500	0.196349	0	0	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	0	0	1.0E-04
2		4	0.3048	0.072966	0	0	1.0E-04
2		12	0.3048	0.072966	0	0	1.0E-04
2		72	0.1151	0.010410	0	0	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	0	0	1.0E-04
3		4	0.3048	0.072966	0	0	1.0E-04
3		12	0.3556	0.099315	0	0	1.0E-04
3		2	0.500	0.196349	0	0	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	0	0	1.0E-04
4		4	0.4064	0.1297	0	0	1.0E-04
4		12	0.3556	0.099315	0	0	1.0E-04
4		72	0.1151	0.010410	0	0	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	0	0	1.0E-04
5		4	0.4064	0.1297	0	0	1.0E-04
5		12	0.3556	0.099315	0	0	1.0E-04
5		2	0.600	0.282740	0	0	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	0	0	1.0E-04
From turbine to HTR							
7	4	2	0.800	0.502650	0	0	1.0E-04
7		2	1.450	1.6280	0	0	1.0E-04
7	130896		0.0030	0.000090	0	0	1.0E-04
7		72	0.2811	0.048750	0	0	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0	0	1.0E-04
8	130896		0.0030	0.000090	0	0	1.0E-04
8		4	0.2400	1.309000	0	0	1.0E-04
8		2	0.800	0.502650	0	0	1.0E-04
8		2	1.450	1.6280	0	0	1.0E-04
8	99900		0.0030	0.000090	0	0	1.0E-04
8		72	0.2228	0.039000	0	0	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0	0	1.0E-04
9	99900		0.0030	0.000090	0	0	1.0E-04
9		4	0.2400	0.999000	0	0	1.0E-04
9		2	0.800	0.502650	0	0	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	0	0	1.0E-04
10		2	1.098	0.8630	0	0	1.0E-04
10	37038		0.0030	0.000090	0	0	1.0E-04
10		72	0.1576	0.019500	0	0	1.0E-04
From split T junction to recomb. comp.							
11	1	2	0.600	0.282740	0	0	1.0E-04
From recomb. comp. to merge T junction							
12	1	2	0.4191	0.137951	0	0	1.0E-04

Figure 6.1: CYCLES II Job 1 Run 1 input—no pipe or plena pressure drops

====CYCLES II INPUT: Job 1 Run 2====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0	0	1.0E-04
1	37038		0.0030	0.000090	0	0	1.0E-04
1		4	0.2400	0.360000	0	0	1.0E-04
1		2	0.500	0.196349	0	0	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0	0	1.0E-04
2		72	0.1151	0.010410	0	0	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	0	0	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0	0	1.0E-04
3		2	0.500	0.196349	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0	0	1.0E-04
4		72	0.1151	0.010410	0	0	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	0	0	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0	0	1.0E-04
5		2	0.600	0.282740	4.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	4.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.800	0.502650	0	0	1.0E-04
7		2	1.450	1.6280	0	0	1.0E-04
7	130896		0.0030	0.000090	0	0	1.0E-04
7		72	0.2811	0.048750	0	0	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0	0	1.0E-04
8	130896		0.0030	0.000090	0	0	1.0E-04
8		4	0.2400	1.309000	0	0	1.0E-04
8		2	0.800	0.502650	0	0	1.0E-04
8		2	1.450	1.6280	0	0	1.0E-04
8	99900		0.0030	0.000090	0	0	1.0E-04
8		72	0.2228	0.039000	0	0	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0	0	1.0E-04
9	99900		0.0030	0.000090	0	0	1.0E-04
9		4	0.2400	0.999000	0	0	1.0E-04
9		2	0.800	0.502650	0	0	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	0	0	1.0E-04
10		2	1.098	0.8630	0	0	1.0E-04
10	37038		0.0030	0.000090	0	0	1.0E-04
10		72	0.1576	0.019500	0	0	1.0E-04
From split T junction to recomp. comp.							
11	1	2	0.600	0.282740	0	0	1.0E-04
From recomp. comp. to merge T junction							
12	1	2	0.4191	0.137951	3.3375	1.12	1.0E-04

Figure 6.2: CYCLES II Job 1 Run 2 input—HP pipe pressure drops added

====CYCLES II INPUT: Job 1 Run 3====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0	0	1.0E-04
1	37038		0.0030	0.000090	0	0	1.0E-04
1		4	0.2400	0.360000	0	0	1.0E-04
1		2	0.500	0.196349	0	0	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0.3000	0.40	1.0E-04
2		72	0.1151	0.010410	2.1000	0.70	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	2.1000	0.70	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0.3000	0.40	1.0E-04
3		2	0.500	0.196349	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0.3000	0.40	1.0E-04
4		72	0.1151	0.010410	3.0000	0.70	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	2.5000	0.70	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0.3000	0.40	1.0E-04
5		2	0.600	0.282740	4.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	4.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.800	0.502650	0	0	1.0E-04
7		2	1.450	1.6280	0	0	1.0E-04
7	130896		0.0030	0.000090	0	0	1.0E-04
7		72	0.2811	0.048750	0	0	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0	0	1.0E-04
8	130896		0.0030	0.000090	0	0	1.0E-04
8		4	0.2400	1.309000	0	0	1.0E-04
8		2	0.800	0.502650	0	0	1.0E-04
8		2	1.450	1.6280	0	0	1.0E-04
8	99900		0.0030	0.000090	0	0	1.0E-04
8		72	0.2228	0.039000	0	0	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0	0	1.0E-04
9	99900		0.0030	0.000090	0	0	1.0E-04
9		4	0.2400	0.999000	0	0	1.0E-04
9		2	0.800	0.502650	0	0	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	0	0	1.0E-04
10		2	1.098	0.8630	0	0	1.0E-04
10	37038		0.0030	0.000090	0	0	1.0E-04
10		72	0.1576	0.019500	0	0	1.0E-04
From split T junction to recomp. comp.							
11	1	2	0.600	0.282740	0	0	1.0E-04
From recomp. comp. to merge T junction							
12	1	2	0.4191	0.137951	3.3375	1.12	1.0E-04

Figure 6.3: CYCLES II Job 1 Run 3 input—HP pipe, HP plena pressure drops added

```

=====CYCLES II INPUT: Job 1 Run 4=====
Pipe data (12 sets)
IP Nsec Npipe Dpipe(ip) Apipe(ip) ELpipe(ip) xsi_pipe(ip) rough_pipe(ip)
(m) (m2) (m)
precooler to main compressor
1 4 72 0.1576 0.019500 0 0 1.0E-04
1 37038 0.0030 0.000090 0 0 1.0E-04
1 4 0.2400 0.360000 4.7000 0.80 1.0E-04
1 2 0.500 0.196349 8.8485 1.945 1.0E-04
main compressor to LTR
2 4 2 0.500 0.196349 13.309 1.90 1.0E-04
2 4 0.3048 0.072966 5.5000 0.60 1.0E-04
2 12 0.3048 0.072966 0.3000 0.40 1.0E-04
2 72 0.1151 0.010410 2.1000 0.70 1.0E-04
LTR to merge T junction
3 4 72 0.1151 0.010410 2.1000 0.70 1.0E-04
3 4 0.3048 0.072966 5.5000 0.60 1.0E-04
3 12 0.3556 0.099315 0.3000 0.40 1.0E-04
3 2 0.500 0.196349 2.8290 1.37 1.0E-04
From merge T junction to HTR
4 4 2 0.600 0.282740 14.660 1.87 1.0E-04
4 4 0.4064 0.1297 5.5000 0.60 1.0E-04
4 12 0.3556 0.099315 0.3000 0.40 1.0E-04
4 72 0.1151 0.010410 3.0000 0.70 1.0E-04
From HTR to IHX (reactor)
5 4 72 0.1151 0.010410 2.5000 0.70 1.0E-04
5 4 0.4064 0.1297 5.5000 0.60 1.0E-04
5 12 0.3556 0.099315 0.3000 0.40 1.0E-04
5 2 0.600 0.282740 4.0000 0.50 1.0E-04
From IHX (reactor) to turbine
6 1 2 0.600 0.282740 4.0000 0.50 1.0E-04
From turbine to HTR
7 4 2 0.800 0.502650 7.8765 1.93 1.0E-04
7 2 1.450 1.6280 4.0000 0.80 1.0E-04
7 130896 0.0030 0.000090 0 0 1.0E-04
7 72 0.2811 0.048750 0 0 1.0E-04
From HTR to LTR
8 7 72 0.2491 0.048750 0 0 1.0E-04
8 130896 0.0030 0.000090 0 0 1.0E-04
8 4 0.2400 1.309000 5.5000 0.80 1.0E-04
8 2 0.800 0.502650 11.492 1.93 1.0E-04
8 2 1.450 1.6280 4.0000 0.80 1.0E-04
8 99900 0.0030 0.000090 0 0 1.0E-04
8 72 0.2228 0.039000 0 0 1.0E-04
From LTR to split T junction
9 4 72 0.2228 0.039000 0 0 1.0E-04
9 99900 0.0030 0.000090 0 0 1.0E-04
9 4 0.2400 0.999000 5.5000 0.80 1.0E-04
9 2 0.800 0.502650 4.0386 1.66 1.0E-04
From split T junction to precooler
10 4 2 0.800 0.502650 2.9888 1.37 1.0E-04
10 2 1.098 0.8630 2.0000 0.80 1.0E-04
10 37038 0.0030 0.000090 0 0 1.0E-04
10 72 0.1576 0.019500 0 0 1.0E-04
From split T junction to recomb. comp.
11 1 2 0.600 0.282740 7.2961 1.66 1.0E-04
From recomb. comp. to merge T junction
12 1 2 0.4191 0.137951 3.3375 1.12 1.0E-04

```

Figure 6.4: CYCLES II Job 1 Run 4 input—HP pipe, HP plena and LP pipe pressure drops added

====CYCLES II INPUT: Job 1 Run 5====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0.2800	0.04	1.0E-04
1	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
1		4	0.2400	0.360000	4.7000	0.80	1.0E-04
1		2	0.500	0.196349	8.8485	1.945	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0.3000	0.40	1.0E-04
2		72	0.1151	0.010410	2.1000	0.70	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	2.1000	0.70	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0.3000	0.40	1.0E-04
3		2	0.500	0.196349	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0.3000	0.40	1.0E-04
4		72	0.1151	0.010410	3.0000	0.70	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	2.5000	0.70	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0.3000	0.40	1.0E-04
5		2	0.600	0.282740	4.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	4.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.800	0.502650	7.8765	1.93	1.0E-04
7		2	1.450	1.6280	4.0000	0.80	1.0E-04
7	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
7		72	0.2811	0.048750	0.0800	0.40	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0.2800	0.40	1.0E-04
8	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
8		4	0.2400	1.309000	5.5000	0.80	1.0E-04
8		2	0.800	0.502650	11.492	1.93	1.0E-04
8		2	1.450	1.6280	4.0000	0.80	1.0E-04
8	99900		0.0030	0.000090	0.1000	1.20	1.0E-04
8		72	0.2228	0.039000	0.2800	0.40	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0.2800	0.40	1.0E-04
9	99900		0.0030	0.000090	0.0050	1.20	1.0E-04
9		4	0.2400	0.999000	5.5000	0.80	1.0E-04
9		2	0.800	0.502650	4.0386	1.66	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	2.9888	1.37	1.0E-04
10		2	1.098	0.8630	2.0000	0.80	1.0E-04
10	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
10		72	0.1576	0.019500	0.2800	0.04	1.0E-04
From split T junction to recomp. comp.							
11	1	2	0.600	0.282740	7.2961	1.66	1.0E-04
From recomp. comp. to merge T junction							
12	1	2	0.4191	0.137951	3.3375	1.12	1.0E-04

Figure 6.5: CYCLES II Job 1 Run 5 input—all pipe and plena pressure drops added

====CYCLES II INPUT: Job 2 Run 1====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0.2800	0.04	1.0E-04
1	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
1	4		0.2400	0.360000	4.7000	0.80	1.0E-04
1	2		0.500	0.196349	8.8485	1.945	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0.3000	0.40	1.0E-04
2		72	0.1151	0.010410	2.1000	0.70	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	2.1000	0.70	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0.3000	0.40	1.0E-04
3		2	0.500	0.196349	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0.3000	0.40	1.0E-04
4		72	0.1151	0.010410	3.0000	0.70	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	2.5000	0.70	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0.3000	0.40	1.0E-04
5		2	0.600	0.282740	1.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	1.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.800	0.502650	7.8765	1.93	1.0E-04
7		2	1.450	1.6280	4.0000	0.80	1.0E-04
7	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
7		72	0.2811	0.048750	0.0800	0.40	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0.2800	0.40	1.0E-04
8	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
8		4	0.2400	1.309000	5.5000	0.80	1.0E-04
8		2	0.800	0.502650	11.492	1.93	1.0E-04
8		2	1.450	1.6280	4.0000	0.80	1.0E-04
8	99900		0.0030	0.000090	0.1000	1.20	1.0E-04
8		72	0.2228	0.039000	0.2800	0.40	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0.2800	0.40	1.0E-04
9	99900		0.0030	0.000090	0.0050	1.20	1.0E-04
9		4	0.2400	0.999000	5.5000	0.80	1.0E-04
9		2	0.800	0.502650	4.0386	1.66	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	2.9888	1.37	1.0E-04
10		2	1.098	0.8630	2.0000	0.80	1.0E-04
10	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
10		72	0.1576	0.019500	0.2800	0.04	1.0E-04
From split T junction to recomb. comp.							
11	1	2	0.600	0.282740	7.2961	1.66	1.0E-04
From recomb. comp. to merge T junction							
12	1	2	0.4191	0.137951	3.3375	1.12	1.0E-04

Figure 6.6: Job 2 Run 1 input—normal pipe sizes

====CYCLES II INPUT: Job 2 Run 2====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0.2800	0.04	1.0E-04
1	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
1		4	0.2400	0.360000	4.7000	0.80	1.0E-04
1		2	0.500	0.196349	8.8485	1.945	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0.3000	0.40	1.0E-04
2		72	0.1151	0.010410	2.1000	0.70	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	2.1000	0.70	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0.3000	0.40	1.0E-04
3		2	0.500	0.196349	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0.3000	0.40	1.0E-04
4		72	0.1151	0.010410	3.0000	0.70	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	2.5000	0.70	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0.3000	0.40	1.0E-04
5		2	0.600	0.282740	1.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	1.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.600	0.282741	7.8765	1.93	1.0E-04
7		2	1.450	1.6280	4.0000	0.80	1.0E-04
7	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
7		72	0.2811	0.048750	0.0800	0.40	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0.2800	0.40	1.0E-04
8	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
8		4	0.2400	1.309000	5.5000	0.80	1.0E-04
8		2	0.800	0.502650	11.492	1.93	1.0E-04
8		2	1.450	1.6280	4.0000	0.80	1.0E-04
8	99900		0.0030	0.000090	0.1000	1.20	1.0E-04
8		72	0.2228	0.039000	0.2800	0.40	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0.2800	0.40	1.0E-04
9	99900		0.0030	0.000090	0.0050	1.20	1.0E-04
9		4	0.2400	0.999000	5.5000	0.80	1.0E-04
9		2	0.800	0.502650	4.0386	1.66	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	2.9888	1.37	1.0E-04
10		2	1.098	0.8630	2.0000	0.80	1.0E-04
10	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
10		72	0.1576	0.019500	0.2800	0.04	1.0E-04
From split T junction to recomp. comp.							
11	1	2	0.600	0.282740	7.2961	1.66	1.0E-04
From recomp. comp. to merge T junction							
12	1	2	0.4191	0.137951	3.3375	1.12	1.0E-04

Figure 6.7: Job 2 Run 2 input—pipe 7 change in diameter

====CYCLES II INPUT: Job 2 Run 3====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0.2800	0.04	1.0E-04
1		37038	0.0030	0.000090	0.0050	1.20	1.0E-04
1		4	0.2400	0.360000	4.7000	0.80	1.0E-04
1		2	0.500	0.196349	8.8485	1.945	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0.3000	0.40	1.0E-04
2		72	0.1151	0.010410	2.1000	0.70	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	2.1000	0.70	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0.3000	0.40	1.0E-04
3		2	0.500	0.196349	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0.3000	0.40	1.0E-04
4		72	0.1151	0.010410	3.0000	0.70	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	2.5000	0.70	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0.3000	0.40	1.0E-04
5		2	0.5	0.349063	1.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	1.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.800	0.502650	7.8765	1.93	1.0E-04
7		2	1.450	1.6280	4.0000	0.80	1.0E-04
7		130896	0.0030	0.000090	0.0050	1.20	1.0E-04
7		72	0.2811	0.048750	0.0800	0.40	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0.2800	0.40	1.0E-04
8		130896	0.0030	0.000090	0.0050	1.20	1.0E-04
8		4	0.2400	1.309000	5.5000	0.80	1.0E-04
8		2	0.800	0.502650	11.492	1.93	1.0E-04
8		2	1.450	1.6280	4.0000	0.80	1.0E-04
8		99900	0.0030	0.000090	0.1000	1.20	1.0E-04
8		72	0.2228	0.039000	0.2800	0.40	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0.2800	0.40	1.0E-04
9		99900	0.0030	0.000090	0.0050	1.20	1.0E-04
9		4	0.2400	0.999000	5.5000	0.80	1.0E-04
9		2	0.800	0.502650	4.0386	1.66	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	2.9888	1.37	1.0E-04
10		2	1.098	0.8630	2.0000	0.80	1.0E-04
10		37038	0.0030	0.000090	0.0050	1.20	1.0E-04
10		72	0.1576	0.019500	0.2800	0.04	1.0E-04
From split T junction to recomp. comp.							
11	1	2	0.600	0.282740	7.2961	1.66	1.0E-04
From recomp. comp. to merge T junction							
12	1	2	0.4191	0.137951	3.3375	1.12	1.0E-04

Figure 6.8: Job 2 Run 3 input—pipe 5 change in diameter

====CYCLES II INPUT: Job 2 Run 4====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0.2800	0.04	1.0E-04
1	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
1		4	0.2400	0.360000	4.7000	0.80	1.0E-04
1		2	0.500	0.196349	8.8485	1.945	1.0E-04
main compressor to LTR							
2	4	2	0.500	0.196349	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0.3000	0.40	1.0E-04
2		72	0.1151	0.010410	2.1000	0.70	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	2.1000	0.70	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0.3000	0.40	1.0E-04
3		2	0.500	0.196349	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.600	0.282740	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0.3000	0.40	1.0E-04
4		72	0.1151	0.010410	3.0000	0.70	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	2.5000	0.70	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0.3000	0.40	1.0E-04
5		2	0.600	0.282740	1.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.600	0.282740	1.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.57	0.251325	7.8765	1.93	1.0E-04
7		2	1.450	1.6280	4.0000	0.80	1.0E-04
7	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
7		72	0.2811	0.048750	0.0800	0.40	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0.2800	0.40	1.0E-04
8	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
8		4	0.2400	1.309000	5.5000	0.80	1.0E-04
8		2	0.57	0.251325	11.492	1.93	1.0E-04
8		2	1.450	1.6280	4.0000	0.80	1.0E-04
8	99900		0.0030	0.000090	0.1000	1.20	1.0E-04
8		72	0.2228	0.039000	0.2800	0.40	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0.2800	0.40	1.0E-04
9	99900		0.0030	0.000090	0.0050	1.20	1.0E-04
9		4	0.2400	0.999000	5.5000	0.80	1.0E-04
9		2	0.57	0.251325	4.0386	1.66	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	2.9888	1.37	1.0E-04
10		2	1.098	0.8630	2.0000	0.80	1.0E-04
10	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
10		72	0.1576	0.019500	0.2800	0.04	1.0E-04
From split T junction to recomb. comp.							
11	1	2	0.600	0.282740	7.2961	1.66	1.0E-04
From recomb. comp. to merge T junction							
12	1	2	0.4191	0.137951	3.3375	1.12	1.0E-04

Figure 6.9: Job 2 Run 4 input—diameter changes for pipes 7, 8, and 9

====CYCLES II INPUT: Job 2 Run 5====

Pipe data (12 sets)

IP	Nsec	Npipe	Dpipe(ip) (m)	Apipe(ip) (m2)	ELpipe(ip) (m)	xsi_pipe(ip)	rough_pipe(ip)
precooler to main compressor							
1	4	72	0.1576	0.019500	0.2800	0.04	1.0E-04
1	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
1		4	0.2400	0.360000	4.7000	0.80	1.0E-04
1		2	0.500	0.196349	8.8485	1.945	1.0E-04
main compressor to LTR							
2	4	2	0.35	0.098175	13.309	1.90	1.0E-04
2		4	0.3048	0.072966	5.5000	0.60	1.0E-04
2		12	0.3048	0.072966	0.3000	0.40	1.0E-04
2		72	0.1151	0.010410	2.1000	0.70	1.0E-04
LTR to merge T junction							
3	4	72	0.1151	0.010410	2.1000	0.70	1.0E-04
3		4	0.3048	0.072966	5.5000	0.60	1.0E-04
3		12	0.3556	0.099315	0.3000	0.40	1.0E-04
3		2	0.35	0.098175	2.8290	1.37	1.0E-04
From merge T junction to HTR							
4	4	2	0.42	0.141370	14.660	1.87	1.0E-04
4		4	0.4064	0.1297	5.5000	0.60	1.0E-04
4		12	0.3556	0.099315	0.3000	0.40	1.0E-04
4		72	0.1151	0.010410	3.0000	0.70	1.0E-04
From HTR to IHX (reactor)							
5	4	72	0.1151	0.010410	2.5000	0.70	1.0E-04
5		4	0.4064	0.1297	5.5000	0.60	1.0E-04
5		12	0.3556	0.099315	0.3000	0.40	1.0E-04
5		2	0.42	0.141370	1.0000	0.50	1.0E-04
From IHX (reactor) to turbine							
6	1	2	0.42	0.282740	1.0000	0.50	1.0E-04
From turbine to HTR							
7	4	2	0.800	0.502650	7.8765	1.93	1.0E-04
7		2	1.450	1.6280	4.0000	0.80	1.0E-04
7	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
7		72	0.2811	0.048750	0.0800	0.40	1.0E-04
From HTR to LTR							
8	7	72	0.2491	0.048750	0.2800	0.40	1.0E-04
8	130896		0.0030	0.000090	0.0050	1.20	1.0E-04
8		4	0.2400	1.309000	5.5000	0.80	1.0E-04
8		2	0.800	0.502650	11.492	1.93	1.0E-04
8		2	1.450	1.6280	4.0000	0.80	1.0E-04
8	99900		0.0030	0.000090	0.1000	1.20	1.0E-04
8		72	0.2228	0.039000	0.2800	0.40	1.0E-04
From LTR to split T junction							
9	4	72	0.2228	0.039000	0.2800	0.40	1.0E-04
9	99900		0.0030	0.000090	0.0050	1.20	1.0E-04
9		4	0.2400	0.999000	5.5000	0.80	1.0E-04
9		2	0.800	0.502650	4.0386	1.66	1.0E-04
From split T junction to precooler							
10	4	2	0.800	0.502650	2.9888	1.37	1.0E-04
10		2	1.098	0.8630	2.0000	0.80	1.0E-04
10	37038		0.0030	0.000090	0.0050	1.20	1.0E-04
10		72	0.1576	0.019500	0.2800	0.04	1.0E-04
From split T junction to recomb. comp.							
11	1	2	0.600	0.282740	7.2961	1.66	1.0E-04
From recomb. comp. to merge T junction							
12	1	2	0.3	0.068976	3.3375	1.12	1.0E-04

Figure 6.10: Job 2 Run 5 input—diameter changes for pipes 2, 3, 4, 5, 6, 12

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