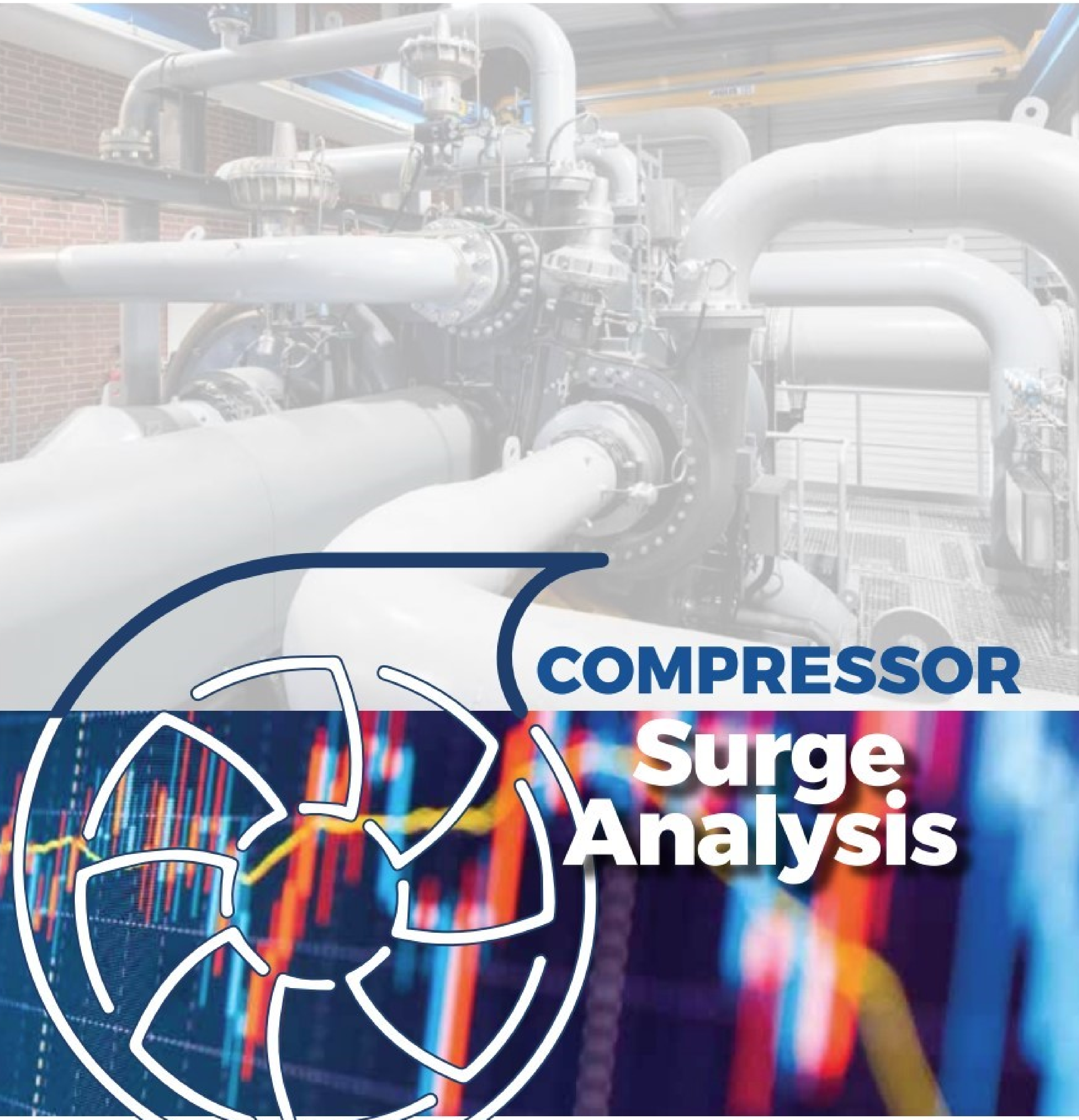

COMPRESSOR Surge Analysis

Ajay S. Satpute

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COMPRESSOR SURGE ANALYSIS

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ABOUT THE AUTHOR

Mr. Ajay S. Satpute is a reputed name in the Chemical Engineering field with 20+ years' experience in several industries like Oil & Gas, Chemicals, Energy, Utilities, Fertilizers, Iron & Steel, and Pulp & Paper etc. in India, the Middle East, and the Far East. He has worked in the process industry in the production, technical services and design department.

He has trained several process engineers in the field of process calculations and simulation.

He is an alumnus of the prestigious Indian Institute of Technology (I.I.T.), Madras with a Master's Degree in Chemical Engineering.

He has shared several process calculation spreadsheets online. Over 50,000+ engineers worldwide have benefited from his spreadsheets, articles and his guidance.

He has also authored a best-selling book on chemical engineering titled "Process Plant Design and Simulation Handbook".

Dedicated to my lovely boy, Sam, who turned 4 this month...

ACKNOWLEDGEMENT

The biggest challenge I faced while writing this book, was to make this difficult topic extremely easy for the readers. It took a total of 13 months to complete the book and most of these months were spent on revision, revision and more revision of the draft. At one point I almost lost the zeal to continue with this project. Fortunately, I had spent enough manhours on it to quit it without a conclusion.

I am truly thankful to the ***CEPL*** process team (Ms. Siddhida Gangan, Mr. Dinesh Kumar S., Mr. Atish Tambe, Mr. Sanket Mahadik, Ms. Alfia Shaikh and Mr. Lijoy Thomas) for their help.

I'm very proud of my elder daughter, Rhea, for working on spell-check, formatting, drawing schematics & tables, numbering the figures & tables after the draft copy of this book was completed.

Alfia, Atish and Rhea have relentlessly checked every step on their own using Aspen ***HYSYS*** software so that there is no error remains in the book. However, if readers find any mistake in any of the chapters, then we all know who to blame. Just kidding!!!

I thank my family (my wife, daughters, mom and sisters) for their constant encouragement and support.

I remember my (late) dad on this day, who, as usual, would have been very proud of me.

Thanks to the Almighty for everything.

Thx.

Ajay S. Satpute

April 2023

PREFACE

Compressor steady-state simulation is one of the simplest topics in chemical engineering. But when it comes to the dynamic simulation model preparation of the compressor system, things become tricky. And when one tries to run scenarios such as normal shutdown or emergency shutdown or start-up cases, then even after several attempts, simulation results are not what one would expect.

For a process engineer, the worst nightmare is when the simulation model doesn't get converged. Compressor surge analysis is capable of giving several such nightmares to our fraternity.

In 2020 I authored a book titled "Process Plant Design and Simulation Handbook". Readers can learn steady-state simulation and dynamic simulation using Aspen HYSYS software with the help of that book. If you have already used it, then only try this book "Compressor Surge Analysis", as this is higher-level stuff.

To effectively use this book, you must have a laptop or pc (with 8 GB RAM or more) with HYSYS installed, a lot of time, patience and motivation to learn. If you don't have any of these items mentioned, then this book is not going to work for you.

Chapter 1 (Centrifugal compressor) explains several terms and concepts related to gas compression.
A centrifugal compression system is modeled in Aspen HYSYS Dynamics in **Chapter 2** (Centrifugal compressor simulation).

Chapter 3 (Centrifugal compressor normal shutdown) explains how to simulate the normal shutdown of a centrifugal compressor.

The emergency shutdown scenario is explained in **Chapter 4** (Centrifugal compressor emergency shutdown).

Chapter 5 (Centrifugal compressor start-up) discusses the start-up scenario.

The adequacy check of an existing ASV is carried out in **Chapter 6** (Adequacy check of existing ASV).

A two-stage compressor simulation model is developed in **Chapter 7** (Real project problem) based on a real project problem. ESD scenario is run to check if the selected ASV sizes are adequate or not.

If the reader has followed the steps given in the book, he/she will be able to carry out surge analysis using Aspen HYSYS Dynamics. And there will be one less reason for the nightmares.

FEED THE ANIMALS INITIATIVE :

You don't find such initiative in a technical book. Nevertheless, as I have been a regular feeder for the last 3 years, I can tell that this is the most satisfying activity that one can do. Hence, I would encourage readers to explore their humanity by feeding the community animals. You cannot feed every animal, but certainly, you can feed a few. That's more than enough.

You can join the following Telegram Group ("Compressor Surge Analysis" to discuss any query that you have) after sharing the book payment receipt and your photo feeding animals.

https://t.me/+eSi3GsRgj5I2Yzdl

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Chapter 1

CENTRIFUGAL COMPRESSOR

The following topics shall be discussed in this chapter;

- Centrifugal Compressor (CC) System
- Performance Map
- Surge & Choked Flow
- Anti-Surge Valve
- Typical Single-Stage CC System
- Compressor Thermodynamic Assessment
- Settle Out Conditions
- System Inertia
- Compressor Shutdown & Startup Scenarios
- Methods To Avoid CC Surge

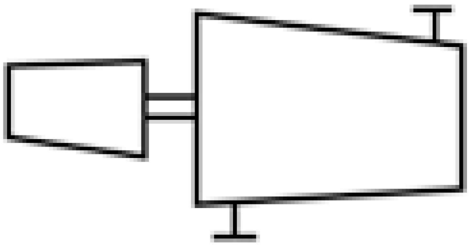
Centrifugal Compressor System

A Compressor is a mechanical device that increases the pressure of gas while reducing its volume. Centrifugal compressors carry out compression action using centrifugal force. Centrifugal force is imparted to the gas mainly through the use of an impeller.

Figure 1.1: Industrial compressor

(Courtesy: www.google.com)

Figure 1.2: Typical representation of turbine-driven centrifugal compressor on a P&ID



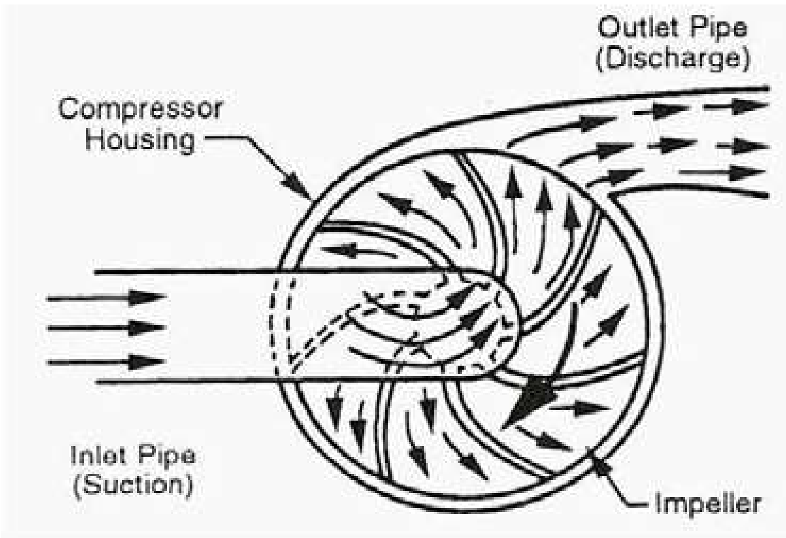
The main components of a CC include:

- Suction pipe
- Impeller
- Compressor casing
- Discharge pipe

The rotating impeller creates a vacuum at the impeller eye. As a result of the vacuum, fresh gas is drawn in via the suction pipe. The gas is then thrown outwards as a result of the centrifugal action caused by impeller rotation. As the gas is ejected, the vacuum is created, allowing more fresh gas to be drawn in via the suction pipe.

The gas circulates around the compressor casing on its way to the discharge pipe. The compressor casing design reduces gas velocity while increasing pressure. Finally, a stream of pressurized gas is forced through the outlet pipe.

Figure 1.3: Schematic of a Centrifugal Compressor



Chapter 2

CENTRIFUGAL COMPRESSOR SIMULATION

Let's simulate a centrifugal compressor system using Aspen HYSYS Dynamics.

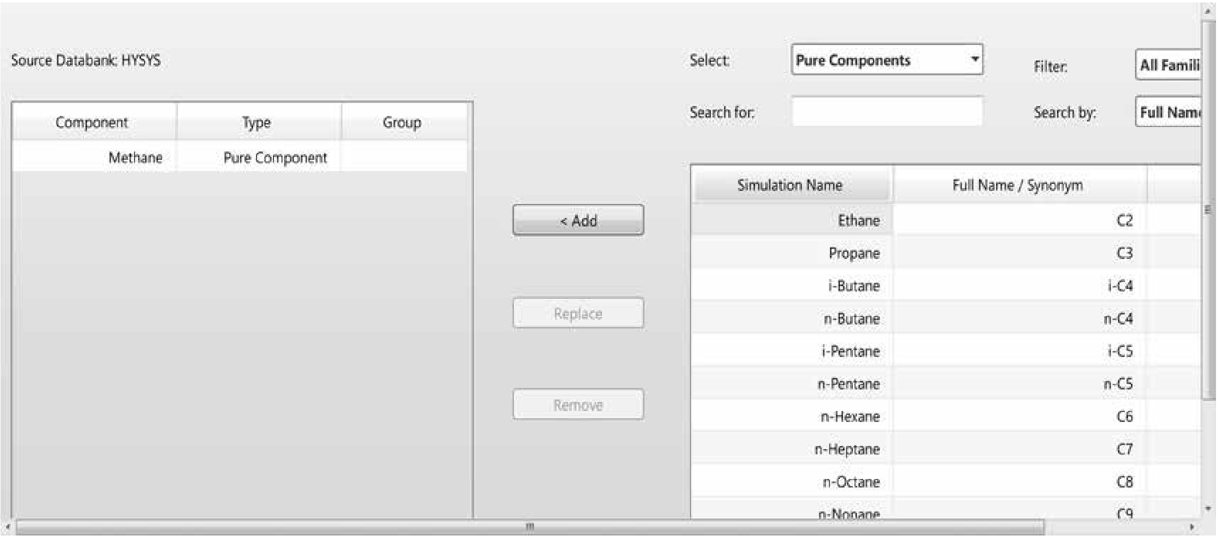
Problem statement:

To compress Methane gas from 7 barg to 16 barg using a centrifugal compressor.

Step 1: Input relevant component(s) into HYSYS

In the "Properties" tab, select "Component Lists" and under "All Items", click "Add" and provide Methane as a pure component.

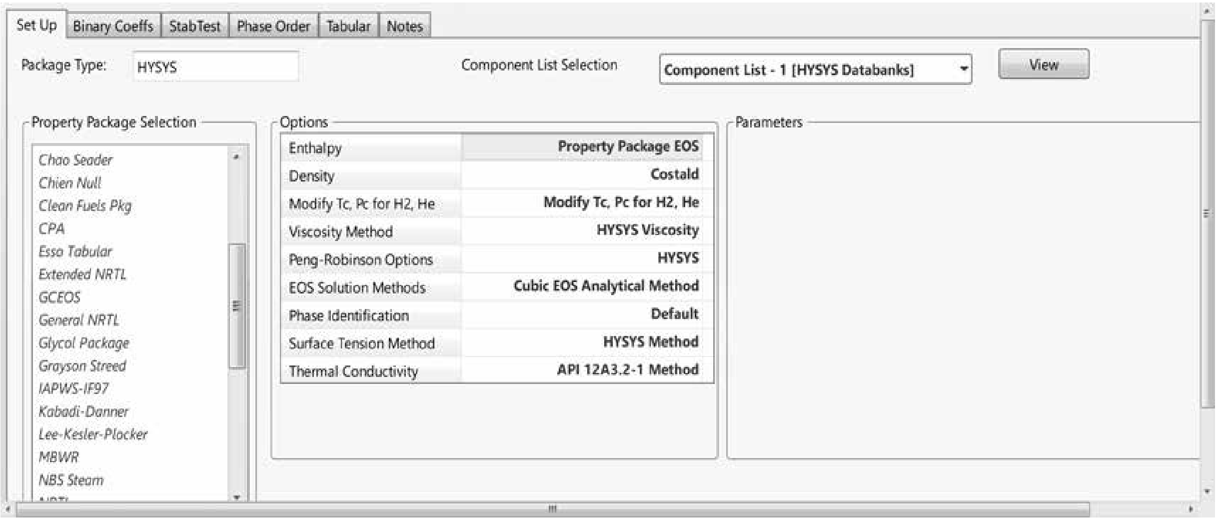
Figure 2.1: Component List



Step 2: Define the Fluid Package

In the "Properties" tab, under "Fluid Packages", click "Add" which directs you to the "Set Up"section, where, "Peng Robinson" shall be selected.

Figure 2.2: Fluid Package



Step 3: Add Material Stream 1

Switch the simulation environment from "Properties" to "Simulation". Input a "Material Stream" from the "Model Palette".

It is advised that the following steps be followed when starting a new simulation file;

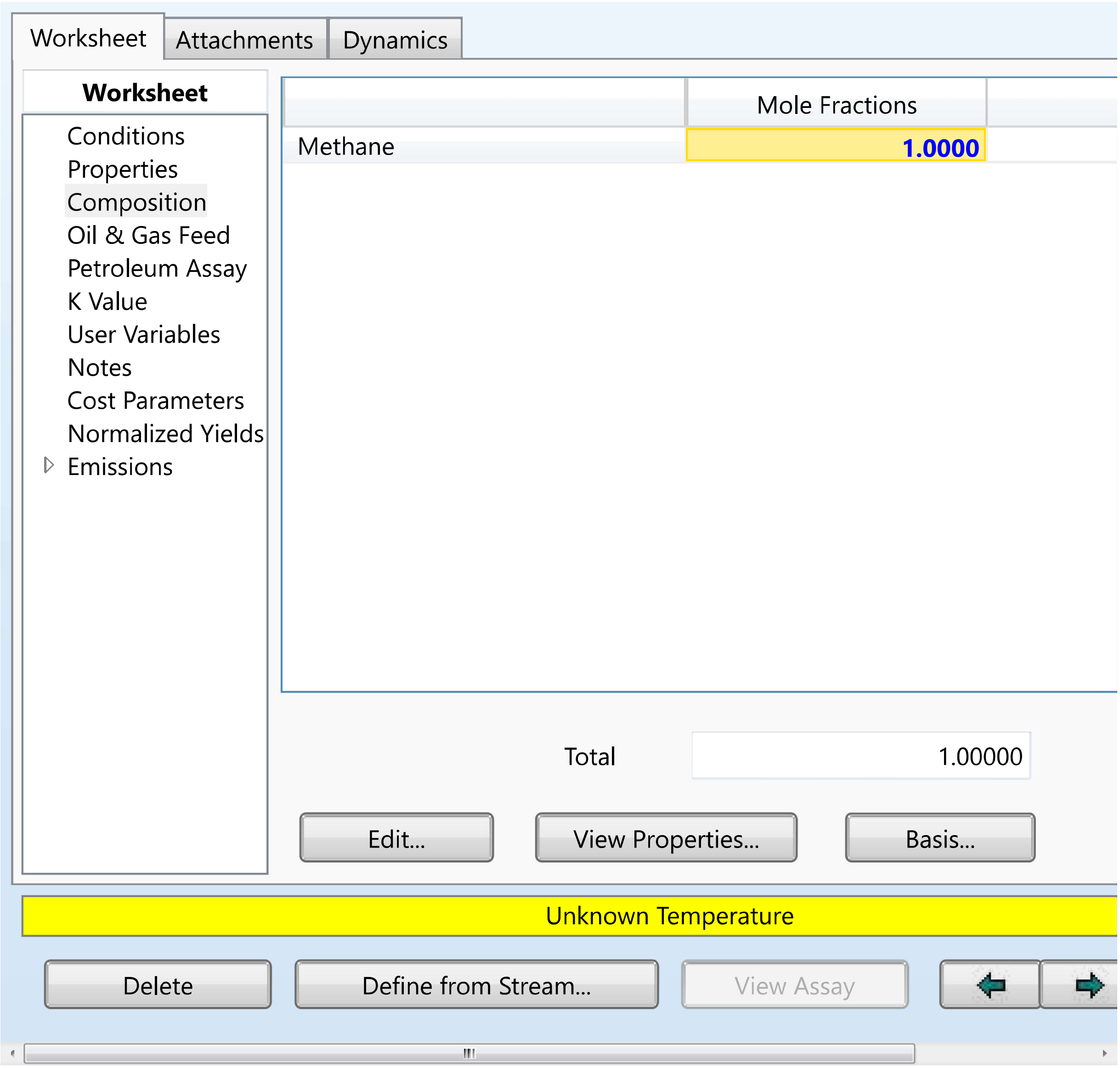
- Go to the top ribbon and click on the "Flowsheet/Modify" tab. Under the "Stream Label" section and check the boxes for "Name", "Temperature", and "Pressure".
- Go to the "Home" tab and set the "Unit Set" to "Safety SI".
- Save the file; "Centrifugal Compressor Simulation" in this case.

Figure 2.3: Material stream 1

Step 4: Define Material Stream 1

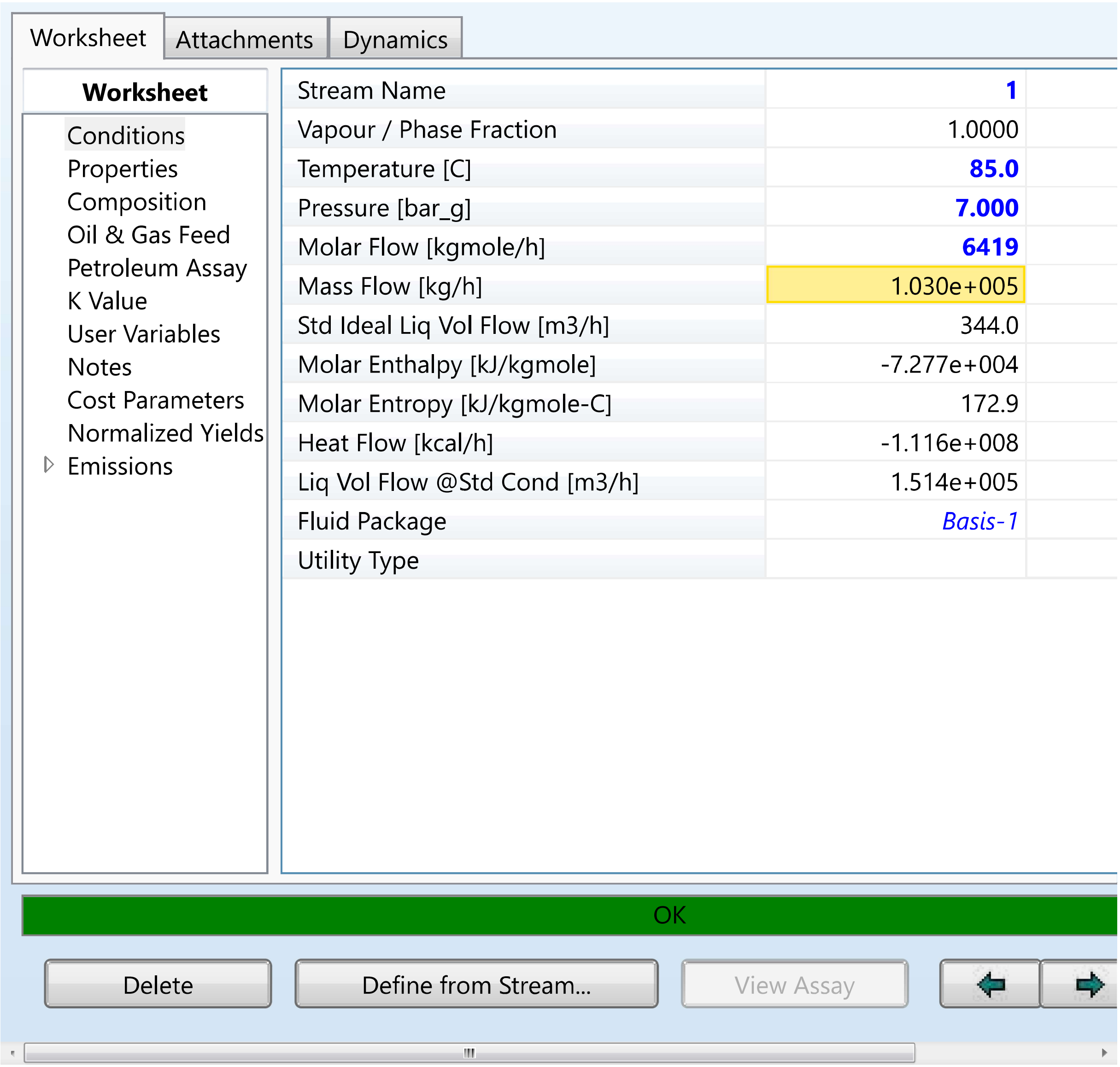
Open material stream 1 (double-click) and under the “Worksheet” tab, select “Composition” and enter the mole fraction value of Methane as 1.

Figure 2.4: Material stream 1 composition



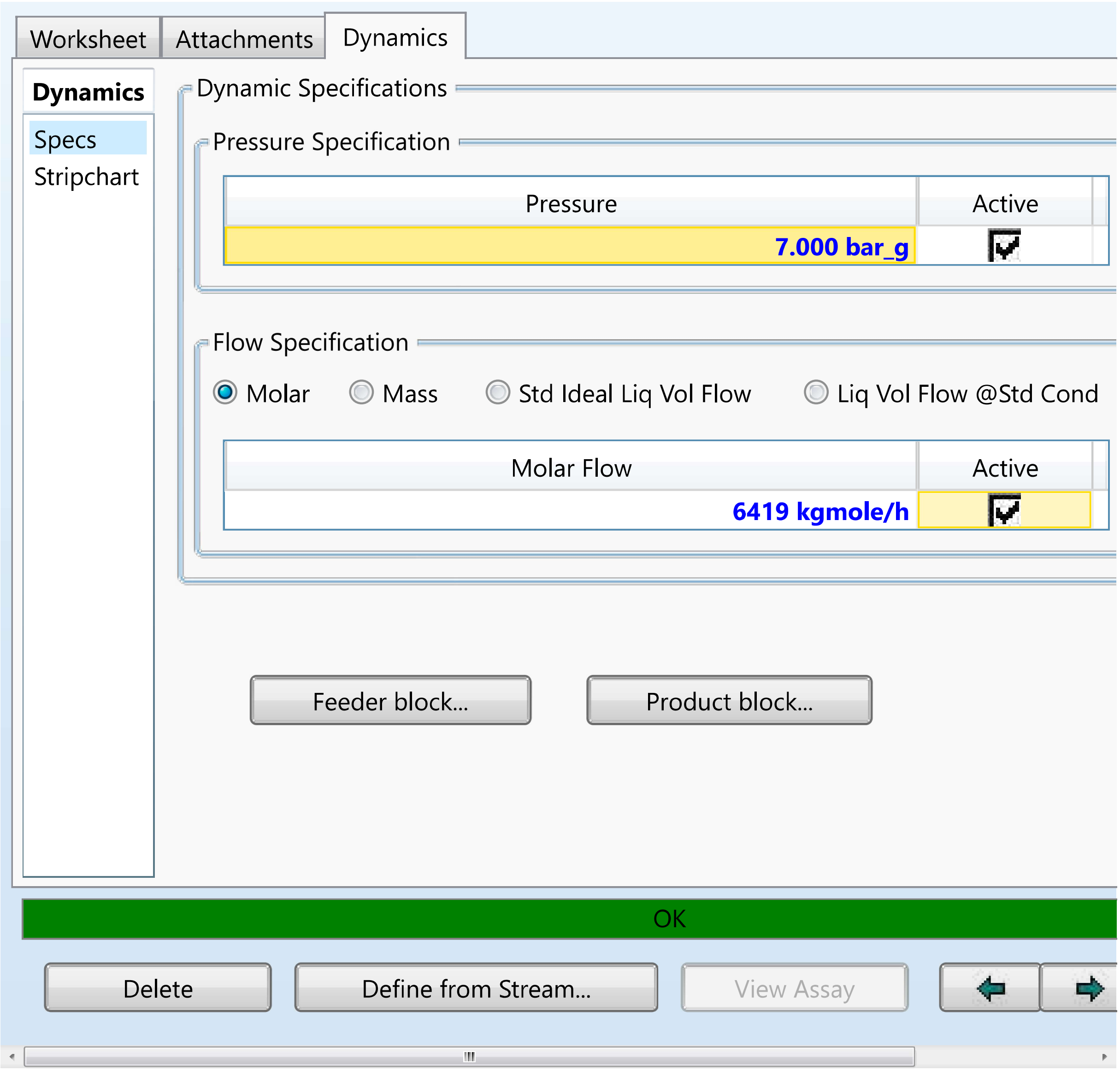
In the same "Worksheet" tab, under "Conditions", enter the values for temperature, pressure, and molar flow as 85 ^{O}C, 7 barg, and 6419 kgmole/h respectively. The material stream will get converged after this step.

Figure 2.5: Material stream 1 conditions



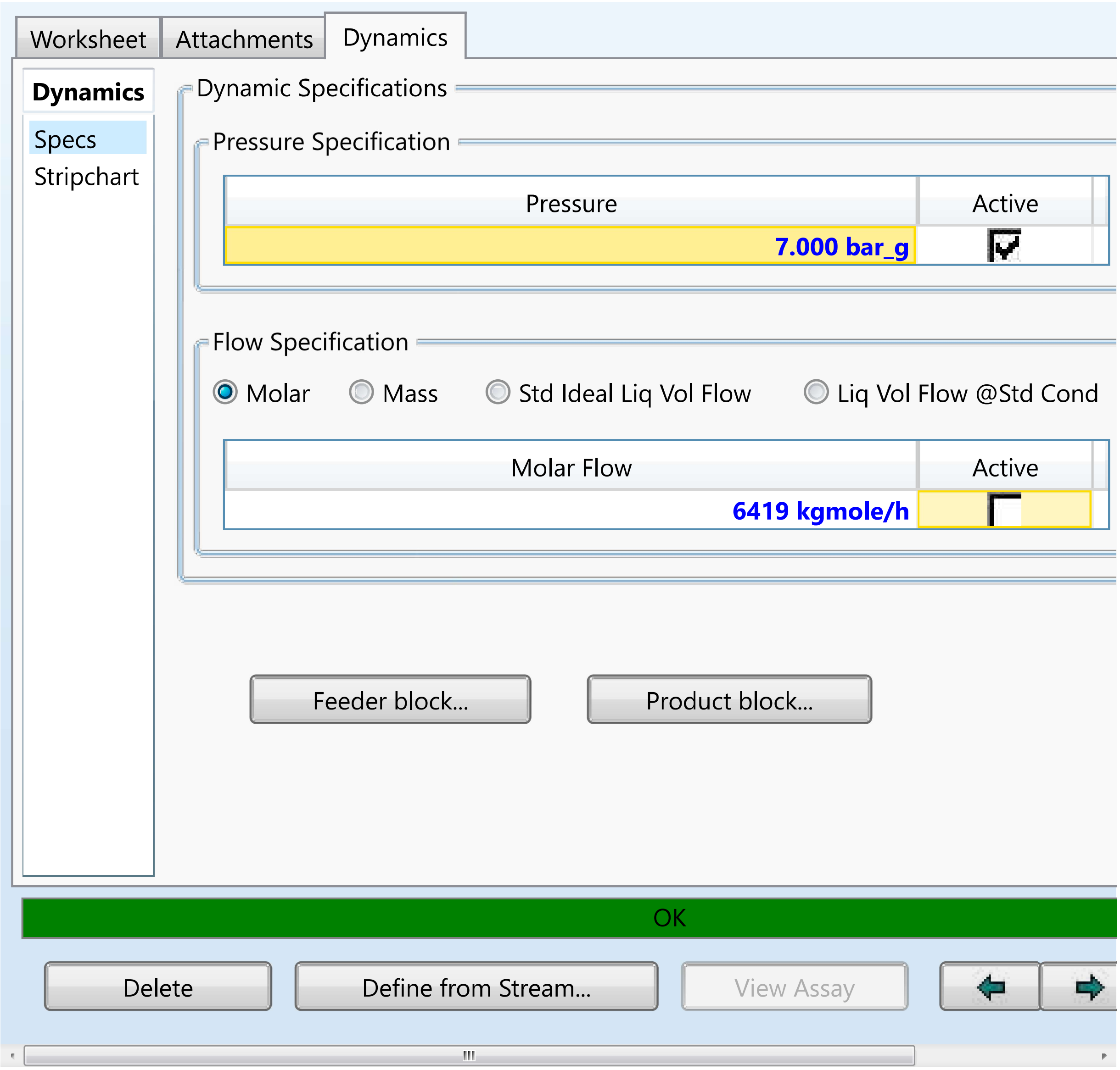
Under the "Dynamics" tab, the checkboxes for both the "Pressure Specification" and the "Flow Specification" box shall be in active mode.

Figure 2.6: Dynamics tab



Deactivate the checkbox for molar flow in the "Flow Specification" section.
Ensure that only the material streams at the boundaries are allowed to be pressure active.

Figure 2.7: Dynamics tab



Note:
The asterisk (*) sign appears only at the streams where pressure specifications are active.

Chapter 3

CENTRIFUGAL COMPRESSOR NORMAL SHUTDOWN

In this chapter, a centrifugal compressor's normal shutdown scenario shall be discussed. In a normal shutdown (NSD) scenario, the operator can choose when to trip the compressor, close the suction & discharge valves and open the ASV.

For a typical NSD operation, the following sequence shall be followed;

a. Run the compressor in steady-state for 5 seconds.

b. After 5 simulation seconds,

   i. The surge controller mode is changed from Auto to Manual.

   ii. The ASV opening is set at 100%.

c. After 6 simulation seconds, the compressor is tripped which is achieved through the following steps,

   i. The pressure controller mode is changed from Auto to Off. Hence, the compressor discharge pressure shall not be maintained at the set pressure value by changing the speed of the compressor.

   ii. The speed controller mode is changed from Cascade to Manual with an OP value of 0%.

   iii. The compressor impeller shall come to rest in say 300 seconds, as per vendor, w.r.to its moment of inertia (225 $kg.m^2$) value. The Friction Loss Factor value is assigned as 0.75 $kg.m^2/s$ (225/300).

d. After 9 simulation seconds,

   i. The Suction SDV and Discharge SDV shall be closed.

A total of 3 simulation cases shall be run for ASVs of 3 different sizes as given below,

   a. ASV with a Cv of 200

   b. ASV with a Cv of 350

   c. ASV with a Cv of 500

At the end of this chapter, the ASV of the appropriate size that is capable of protecting the compressor system from a surge event will be decided.

Let's simulate a centrifugal compressor's normal shutdown scenario using Aspen HYSYS.

Problem statement :

To execute a normal shutdown of a centrifugal compressor that is compressing Methane gas from 7 barg to 16 barg.

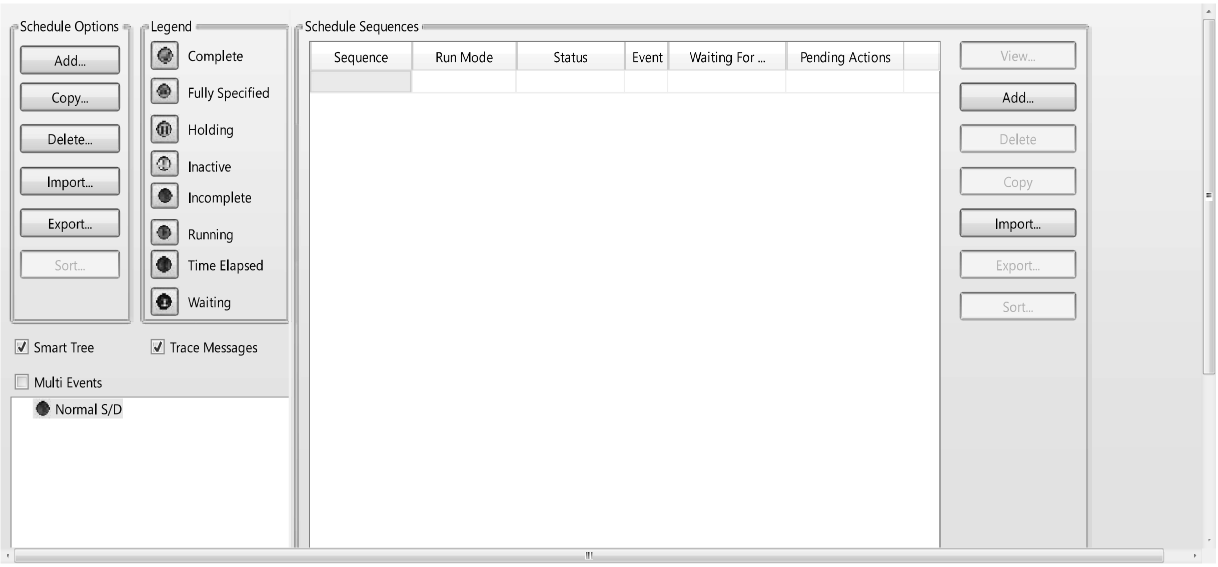
Step 1: Prepare the Compressor Model

Follow steps 1 to 24 from chapter 2 to model the compressor system.

Step 2: Initiate the Event Scheduler

In the top ribbon, open the "Dynamics" tab and select "Event Scheduler". Click the "Add" button in the "Schedule Options" section, and change the schedule name to "Normal S/D".

Figure 3.1: Event Scheduler

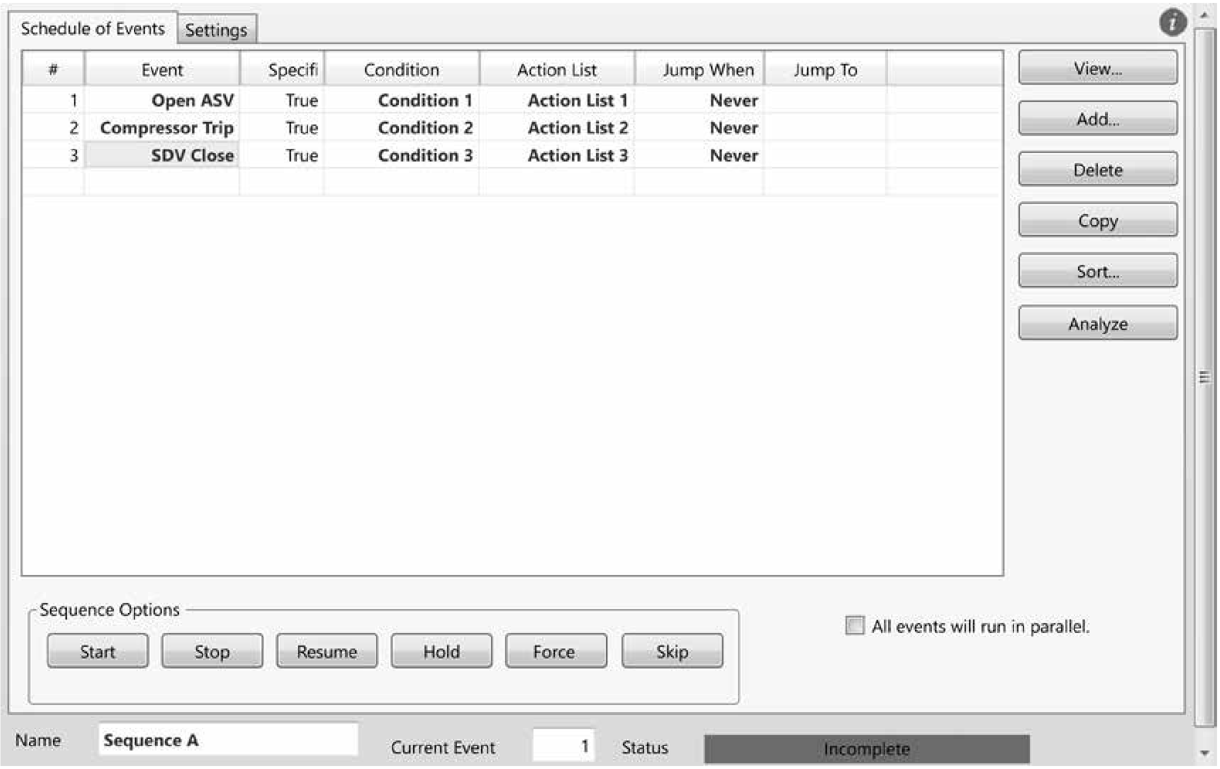


Step 3: Input Events Pertaining to NSD

In the Event Scheduler" window, under "Schedule Sequences", click "Add", which will insert a sequence named "Sequence A" by default. Click "View" which will open a new window where "Add" is clicked to enter the following events.

- Open ASV
- Compressor Trip
- SDV Close

Figure 3.2: Schedule of Events



Chapter 4

CENTRIFUGAL COMPRESSOR EMERGENCY SHUTDOWN

In this chapter, a centrifugal compressor's emergency shutdown scenario shall be discussed. In an emergency shutdown (ESD) scenario, the operator cannot choose when to trip the compressor or open the ASV. The compressor may trip at any given moment due to power failure or a process upset and the Surge Controller will control the ASV opening to prevent surge conditions.

For a typical ESD operation, the following sequence shall be followed;

a. Run the compressor in steady-state for 5 seconds.

b. After 5 simulation seconds, the compressor is tripped which is achieved through the following steps,

    i. The pressure controller mode is changed from Auto to Off. Hence, the compressor discharge pressure shall not be maintained at the set pressure value by changing the speed of the compressor.

    ii. The speed controller mode is changed from Cascade to Manual with an OP value of 0%.

    iii. The compressor impeller shall come to rest in say 300 seconds, as per vendor, w.r.to its moment of inertia (225 kg.m^2) value. The Friction Loss Factor value is assigned as 0.75 kg.m^2/s (225/300).

c. After 7 simulation seconds,

    i. The Suction SDV and Discharge SDV shall be closed.

    A total of 3 simulation cases shall be run for ASVs of 3 different sizes as given below,

    a. ASV with a Cv of 200

    b. ASV with a Cv of 350

    c. ASV with a Cv of 500

At the end of this chapter, the ASV of the appropriate size that is capable of protecting the compressor system from a surge event will be decided.

Let's simulate a centrifugal compressor's emergency shutdown scenario using Aspen HYSYS.

Problem statement:
To execute an emergency shutdown of a centrifugal compressor that is compressing Methane gas from 7 barg to 16 barg.

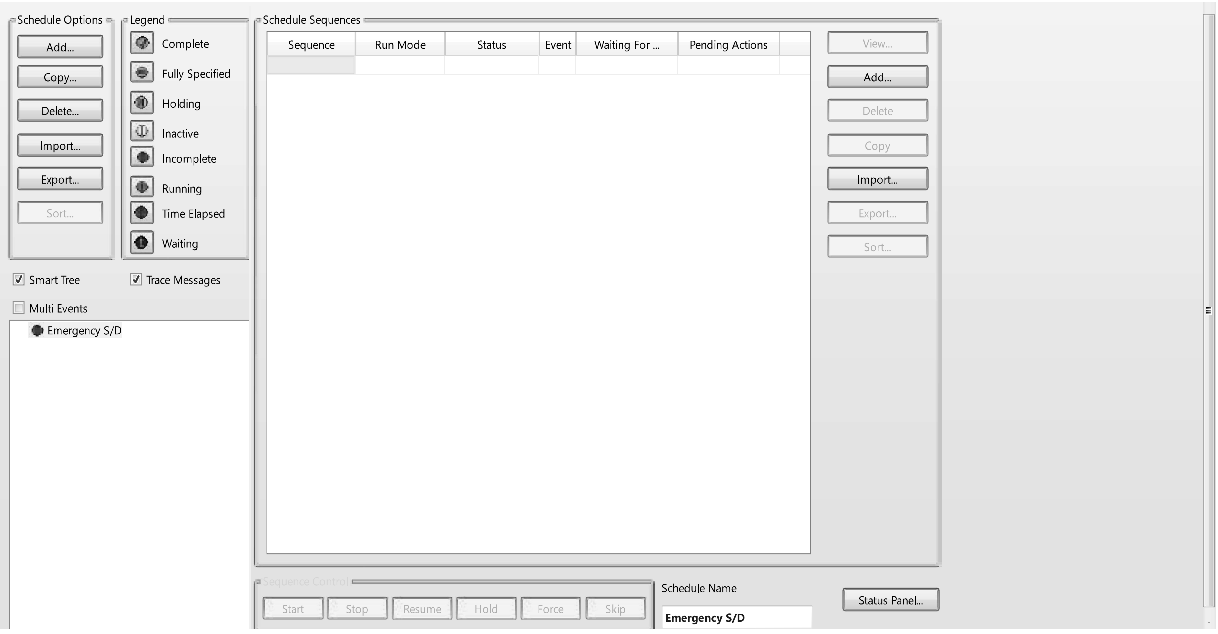
Step 1: Prepare the Compressor Model

Follow steps 1 to 24 from chapter 2 to model the compressor system.

Step 2: Initiate the Event Scheduler

In the top ribbon, open the "Dynamics" tab and select "Event Scheduler". Click the "Add" button in the "Schedule Options" section, and change the schedule name to "Emergency S/D".

Figure 4.1: Event Scheduler

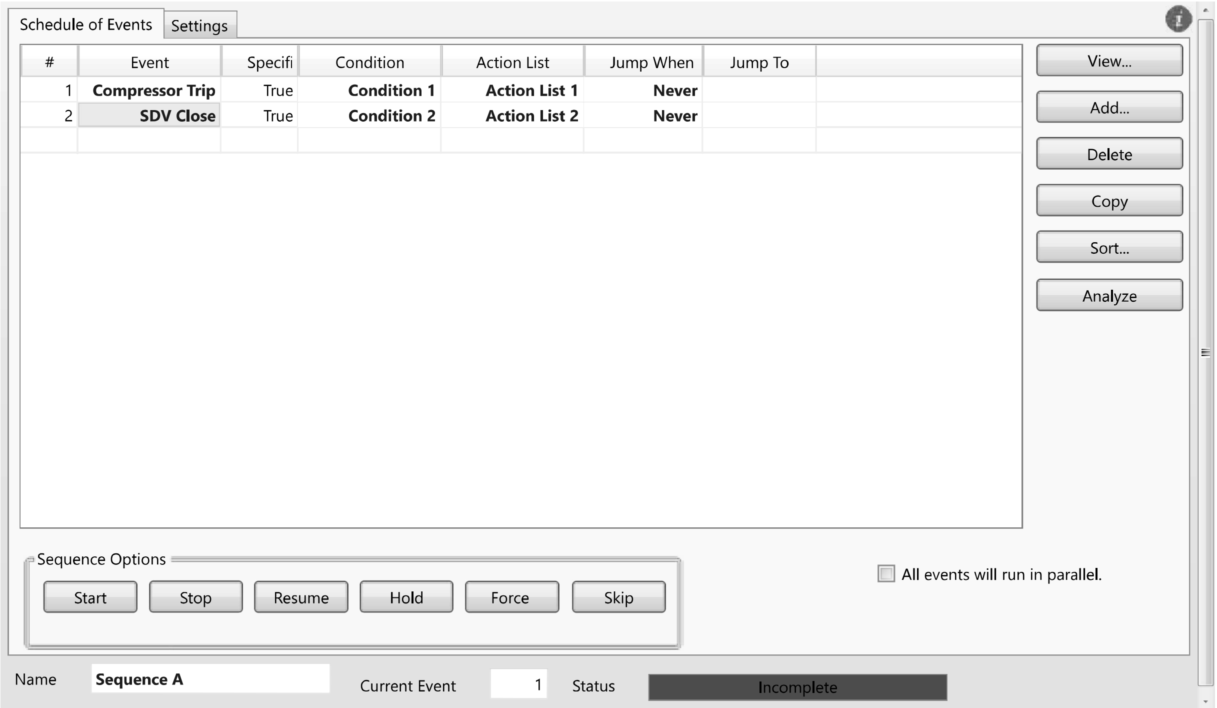


Step 3: Input Events Pertaining to ESD

In the "Event Scheduler" window, under "Schedule Sequences", click "Add", which will insert a sequence named "Sequence A" by default. Click "View" which will open a new window where "Add" is clicked to enter the following events.

- Compressor Trip
- SDV Close

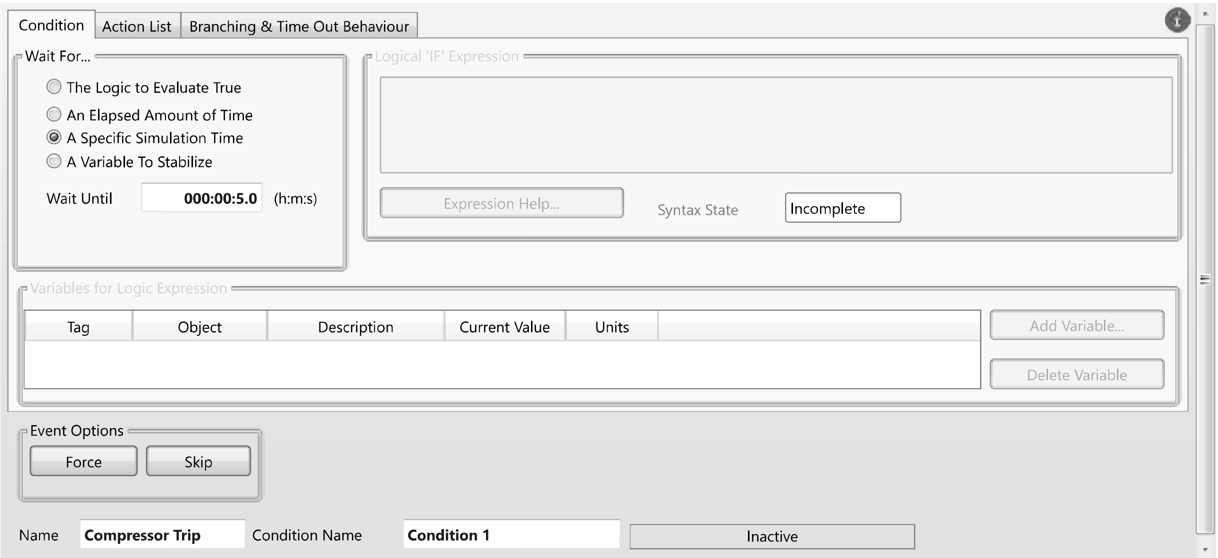
Figure 4.2: Schedule of Events



Step 4: Input Actions For Compressor Trip Event

Open the event "Compressor Trip" (double-click).
Under the "Condition" tab, change the "Wait For" option to "A Specific Simulation Time" and input the "Wait Until" value as 5 seconds.

Figure 4.3: Condition tab



Chapter 5

CENTRIFUGAL COMPRESSOR START - UP

In this chapter, a centrifugal compressor's start-up scenario shall be discussed. In a startup scenario, the operator can choose when to start the compressor and open the suction & discharge valves. It is expected that the surge controller, through the ASV, will prevent the formation of a surge event.

For a typical start-up option, the following sequence shall be followed;

a. The compressor remains in a tripped condition for 5 seconds.
b. After 5 simulation seconds, the compressor is started which is achieved through the following steps,
    i. The pressure controller mode is set to Auto. Hence, the compressor discharge pressure shall be maintained at the set pressure value by changing the speed of the compressor.
    ii. The speed controller mode is set to Cascade.
    iii. The surge controller mode is set to Auto
c. After 25 simulation seconds,
    i. The Suction SDV and Discharge SDV shall be opened.

A total of 3 simulation cases shall be run for ASVs of 3 different sizes as given below,

a. ASV with a Cv of 200
b. ASV with a Cv of 350
c. ASV with a Cv of 500

At the end of this chapter, the ASV of the appropriate size that is capable of protecting the compressor system from a surge event will be decided.

Let's simulate a centrifugal compressor's start-up scenario using Aspen HYSYS.

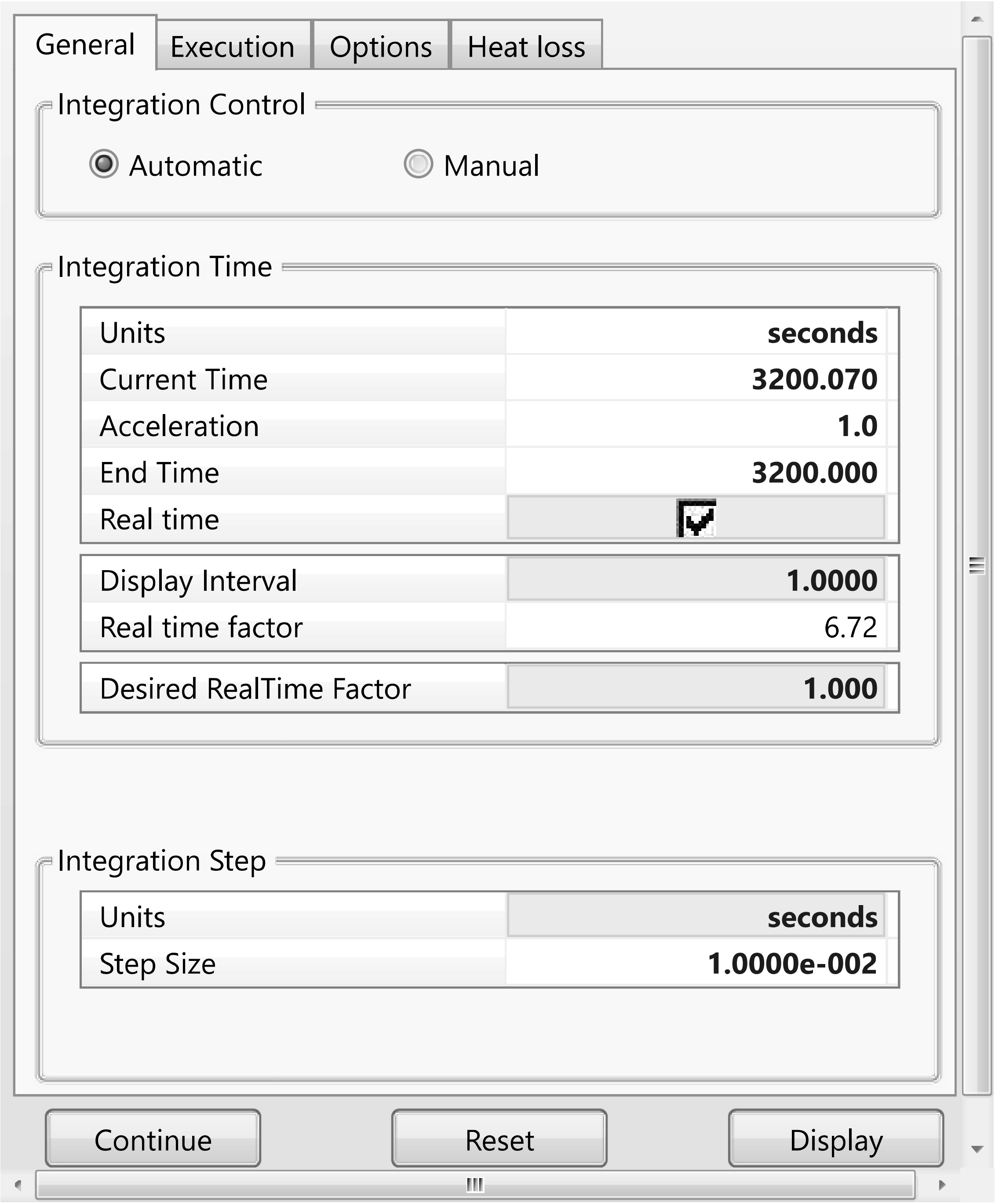
Problem statement:

To simulate the startup of a centrifugal compressor intended to compress Methane gas from 7 barg to 16 barg.

Step 1: Prepare the Compressor Model

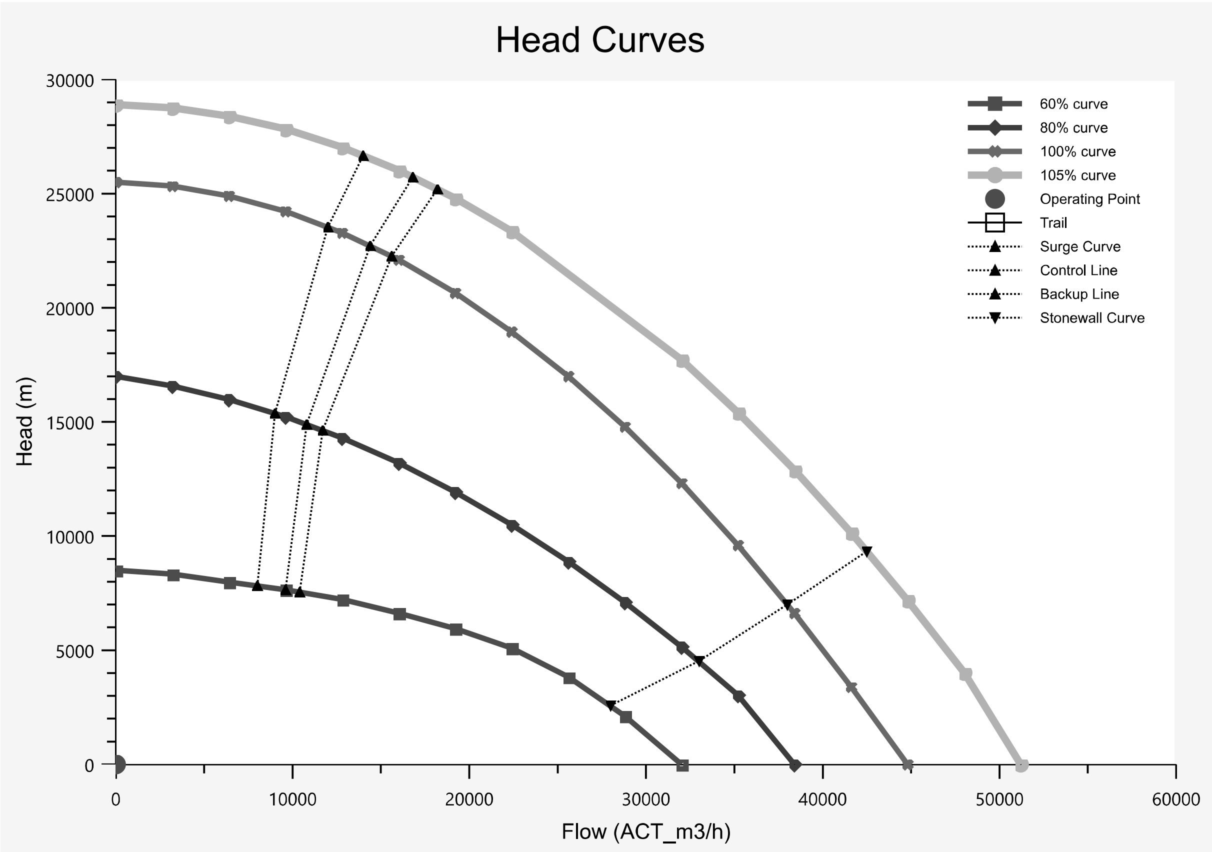
Open any post-run file from either the ESD or the NSD chapter. Open the integrator and input the new "End Time" value as 3200 seconds and click "Continue". The reason for carrying out this exercise is to obtain a compressor model where the compressor is completely stopped, i.e., the operating point is at 0 and the PV value of the speed controller is 0. If that is not achieved in 3200 seconds, then run it for more time.

Figure 5.1: Integrator Window



After the model has completed its run, the operating point on the compressor performance curve graph should be at the origin point. In case the operating point is not at the origin, continue to run the compressor for longer by increasing the "End Time".

Figure 5.2: Compressor Performance Curves Window



Chapter 6

ADEQUACY CHECK OF EXISTING ASV

In this chapter, a centrifugal compressor's dynamic simulation shall be discussed with consideration of piping volume.

The fluid volume downstream of the compressor would determine the size of the ASV required. As the fluid volume increases, which could be a direct result of the pipe length/size, the ASV needed to help redirect that volume back into compressor suction would be of a greater size. As mentioned in chapter 1, a way to mitigate centrifugal compressor surge is to shorten pipe length and minimize pipe volume, which in turn could lead to a smaller ASV requirement.

Let's simulate a centrifugal compressor using Aspen HYSYS.

Problem statement:

To carry out the adequacy check of an existing compressor system with a 4" ASV, while considering piping data, and to study its impact on the size of the ASV during an emergency shutdown scenario.

As mentioned in the problem statement, the system is existing, hence, system data shall be provided by the vendor and/or the client. We are to simulate the system to check its adequacy for an emergency shutdown scenario which is the most conservative case as seen in chapters 3, 4, and 5.

Step 1: Setup the Compressor Model

Open the pre-run file, "ESD_Pre-run_500.hsc" from the emergency shutdown chapter (4) to serve as the base file for this simulation. Ensure that the "Sequence Control" is stopped in "Event Scheduler". Save-as the file under the name "ESD_Pre-run_PipeVol.hsc" for future reference.

Step 2: Incorporate pipe data

In the "Flowsheet", insert a total of 4 "Pipe Segments" (PS) and 1 "Compressed Gas Pipe" (CGP) in the model at the locations given below. Refer to Figure 6.1.

- PS1 shall be placed after the suction SDV, before the ASV line.
- PS2 shall be placed after the Mixer.
- PS3 shall be placed in the compressor discharge, before the Cooler.
- PS4 shall be placed in the compressor discharge, after the discharge SDV.
- CGP-100 shall be placed in the ASV line.

The "Compressible Gas Pipe" is provided on the ASV line to obtain the Mach no. of the fluid. Consider HTC as 0, ambient temperature as 25 ^{O}C and no. of cells as 50.

Input the following data as per piping isometric. After completing each pipe segment, run the model for some time to get a steady value for all the streams.

Table 6.1: Piping Data

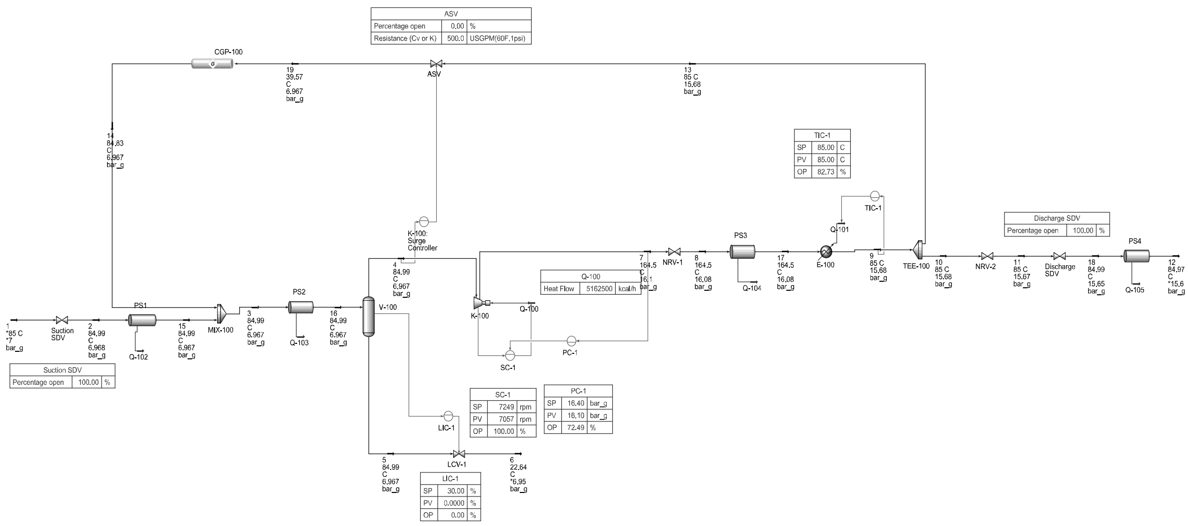
Pipe segment	Length (m)	Elevation (m)	Pipe Schedule	Pipe NB (mm)	Material
PS1	10	0	40	800	Mild Steel
PS2	2	0	40	800	Mild Steel
PS3	5	0	40	450	Mild Steel
PS4	50	0	40	400	Mild Steel
CGP-100	15	0	40	150	Mild Steel

Heat loss/gain (w.r.to ambient) for pipe segments is considered zero.
The following line sizing criteria are used.

- As per best engineering practices, ASV lines are sized on the Mach no. basis with a maximum Mach no. value of 0.3 is allowed.
- And the maximum velocity of gas should be below 30 m/s (as per the client's design basis).

In the "Event Scheduler" tab, under "Schedule", in "Sequence Control", click "Stop". This step will ensure that there is no shutdown occurs. Once all info has been provided for the pipes, the model shall be run until we get the steady values.

Figure 6.1: HYSYS model after adding PS and CGP



Step 3: Incorporate existing ASV data

ASV data is obtained from the vendor datasheet and is tabulated below for 2 valves, one with a Cv of 193 (4") and the other with a Cv of 453 (6").

In the existing system, the ASV provided is the one with a Cv of 193. An adequacy check shall be carried out for the existing ASV first.

Table 6.2: ASV Data

% Valve opening	Cv % for model 1 with Cv = 193	Cv % for model 2 with Cv = 453
0	0	0
5	8	7
10	16	13
20	35	28
30	53	44
40	68	56
50	79	67
60	85	76
70	88	85
80	91	91
90	95	96
100	100	100

Chapter 7

REAL PROJECT PROBLEM

In this chapter, a real project problem concerning a two-stage centrifugal compressor's dynamic simulation shall be discussed. The input data, flow scheme, and other miscellaneous values considered shall be more in-line with what one would come across on the job.

A compressor unit rarely consists of just one compressor working to raise the gas pressure to the desired value. Instead, compression is carried out in multiple steps or stages, referred to as multi-stage compression. Each stage comprises a compressor and a cooler. The gas passes through the first stage where the gas pressure is raised to an intermediate level before being directed to the next stage. The gas exiting the final stage is brought up to the desired pressure. Each stage would employ an ASV dedicated to preventing surge for that stage.

Let's simulate a centrifugal compressor using Aspen HYSYS.

Problem statement:

A gas mixture, available at 9076 kg/h and 24 ^{O}C, is to be compressed from 3 barg to 29 barg using a two-stage centrifugal compressor. The compressed gas shall be provided at 24 ^{O}C as well. The feedstock composition is given below. Simulate the system for the emergency shutdown scenario.

Table 7.1: Feed gas composition

Sr. No.	Component	Mole Fraction
1	Nitrogen	0.0010
2	Carbon Dioxide	0.0097
3	Methane	0.8443
4	Ethane	0.0600
5	Propane	0.0300
6	i-Butane	0.0150
7	n-Butane	0.0150
8	i-Pentane	0.0100
9	n-Pentane	0.0100
10	n-Hexane	0.0050

Step 1: Provide HYSYS with the given input data

In the "Properties" tab, select all the components provided in Table 7.1 as pure components, following which, assign Peng-Robinson as the fluid package. Open the simulation, allocate a material stream as the feed stream and provide the rest of the input data available in the problem statement. Use "Safety SI" as Unit Set.

Figure 7.1: Feed stream conditions

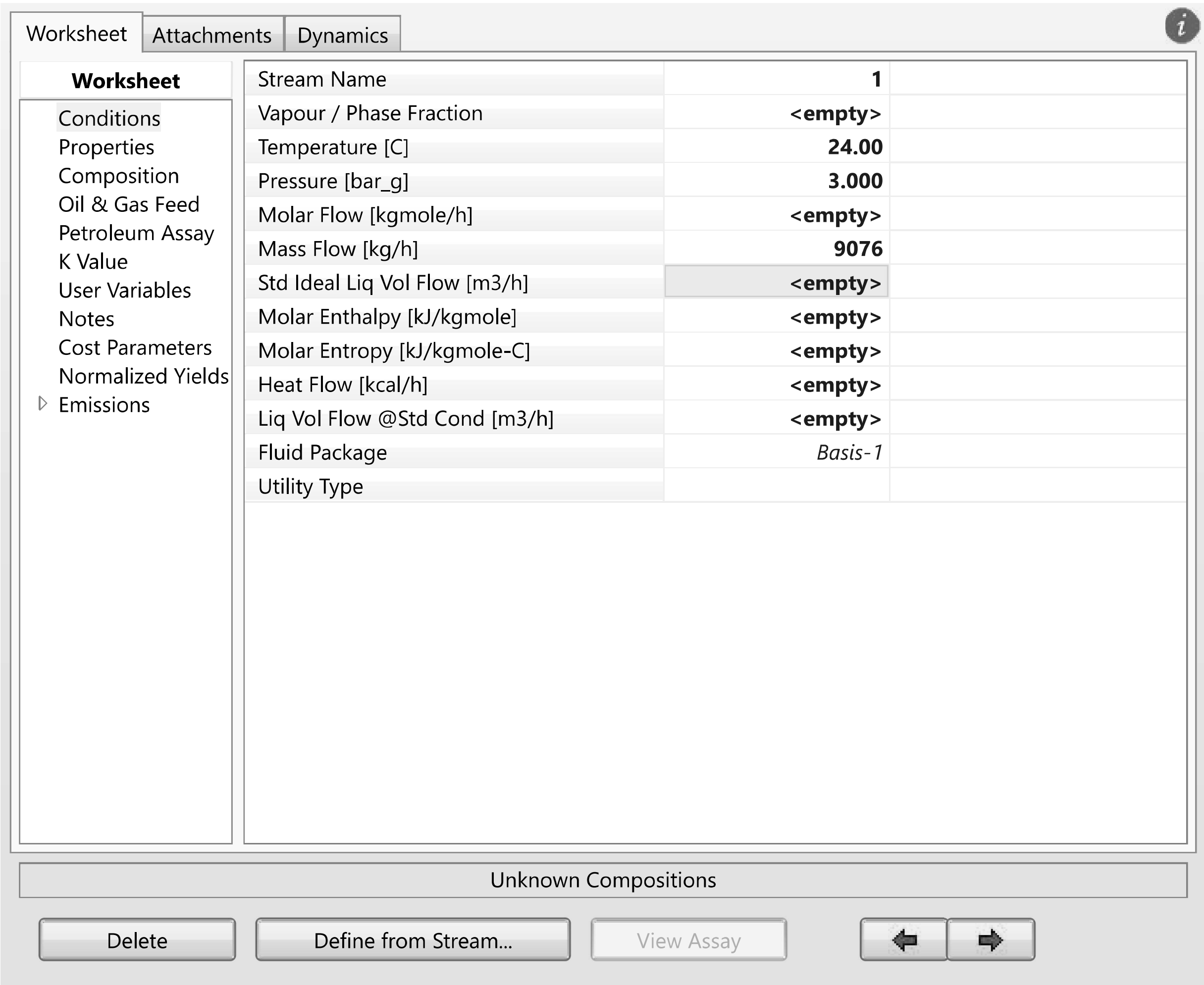
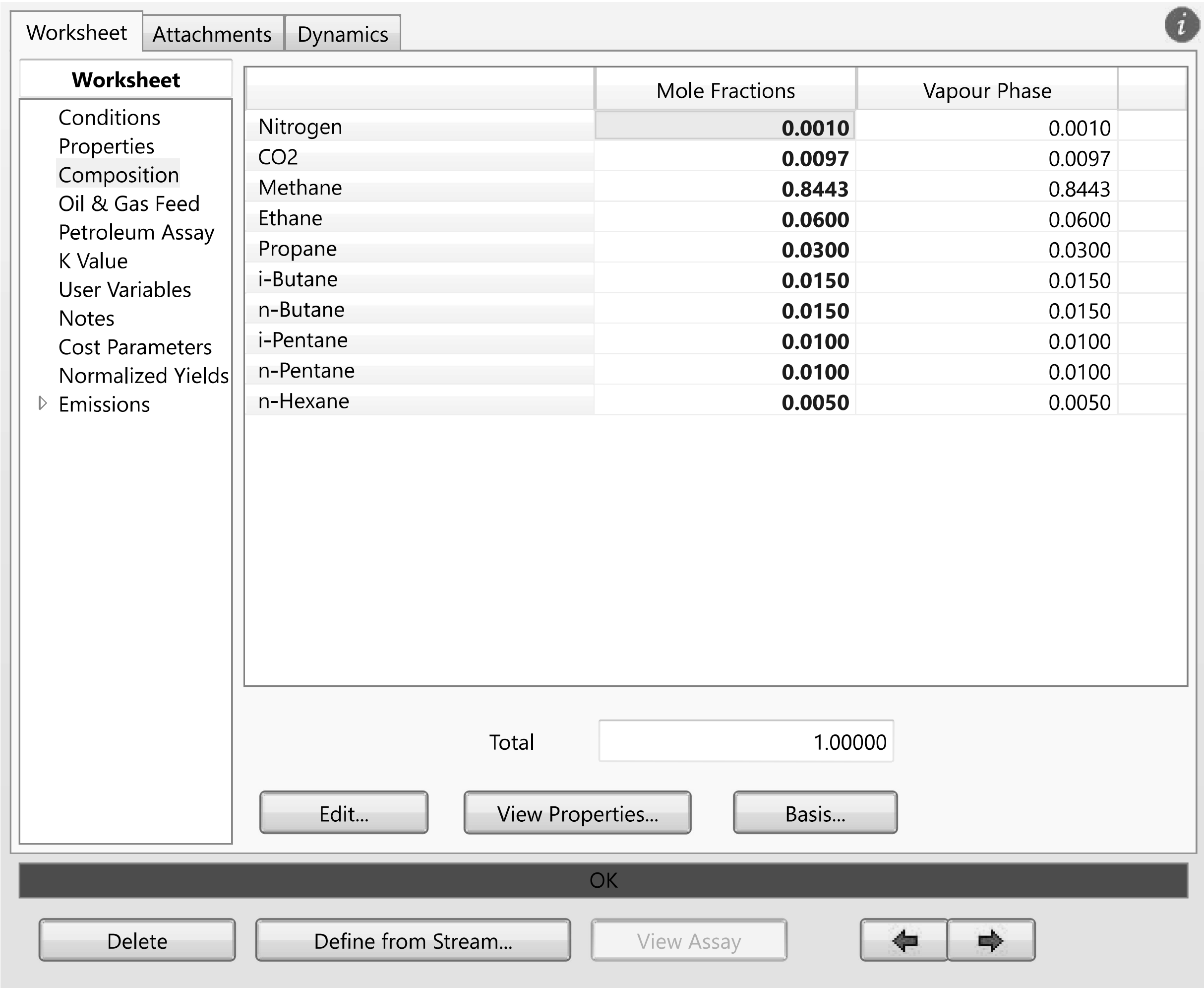


Figure 7.2: Feed gas composition



	Mole Fractions	Vapour Phase
Nitrogen	**0.0010**	0.0010
CO2	**0.0097**	0.0097
Methane	**0.8443**	0.8443
Ethane	**0.0600**	0.0600
Propane	**0.0300**	0.0300
i-Butane	**0.0150**	0.0150
n-Butane	**0.0150**	0.0150
i-Pentane	**0.0100**	0.0100
n-Pentane	**0.0100**	0.0100
n-Hexane	**0.0050**	0.0050

Step 4: Designate the compressor

Provide a compressor from the model palette and make the appropriate connections as done in the earlier chapters.

Figure 7.5: Compressor Flowsheet

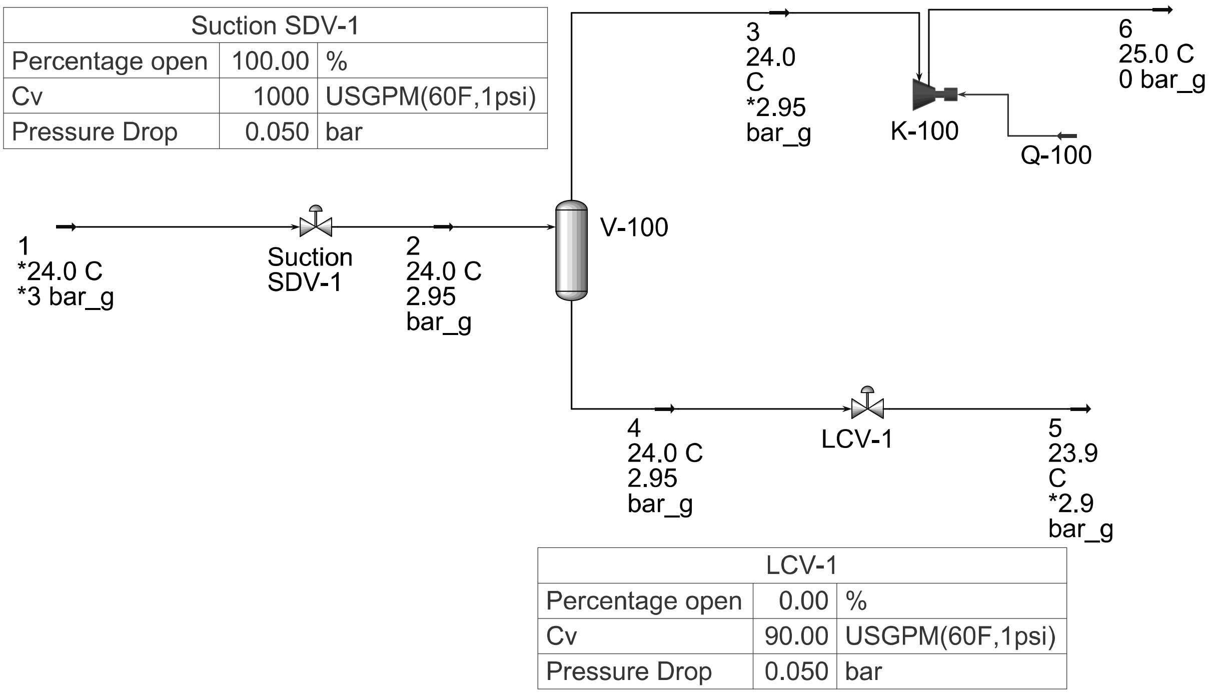
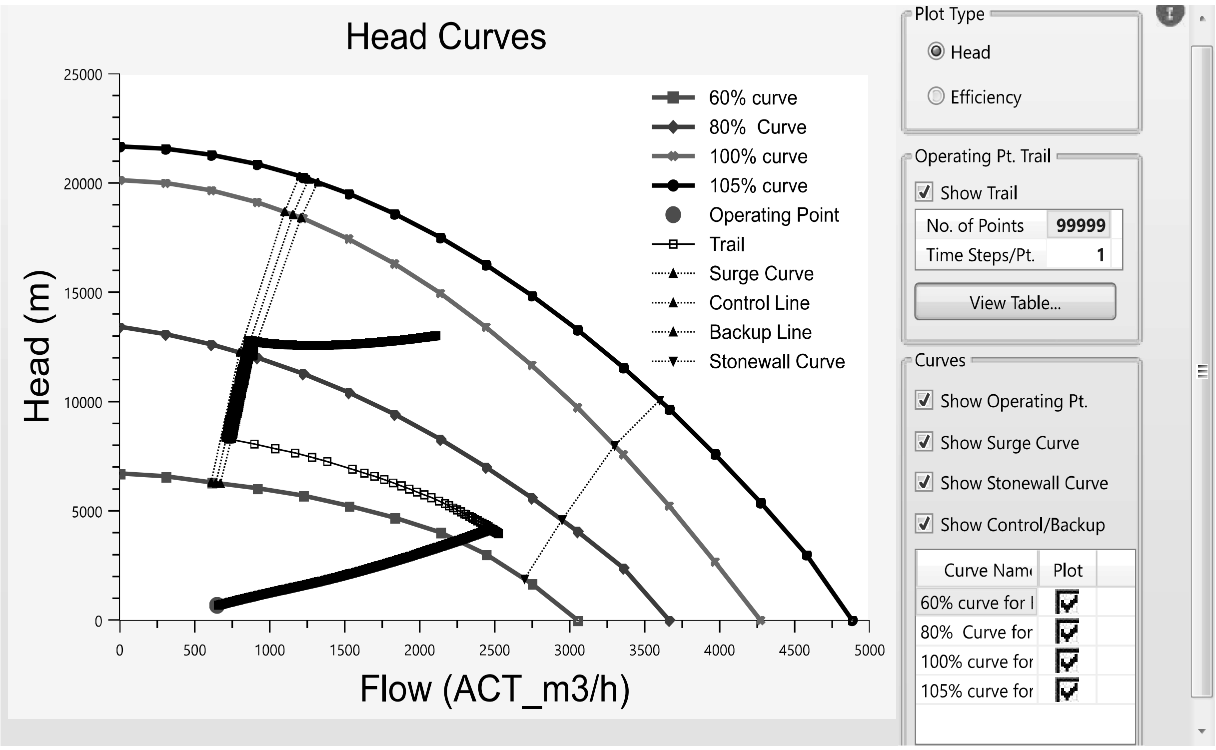


Figure 7.70: Performance curve – K-100



Shown below is the curve for the second-stage compressor. It is evident that surge flow does not occur since the operating point does not cross the surge curve at any point. Hence, it may be concluded that the ASV provided for the second compressor is sufficiently sized as well.

COMPRESSOR SURGE ANALYSIS

This book provides the step-by-step procedure to build a dynamic model of the Centrifugal Compressor. Compressor normal shut-down, emergency shut-down and start-up scenarios are demonstrated using Aspen HYSYS simulation software.

With the help of this book, the reader can carry out compressor surge analysis of the existing system and conclude if the size of the ASV is adequate or not. Also, the reader can recommend the ASV size for the new system.

Ajay S. Satpute

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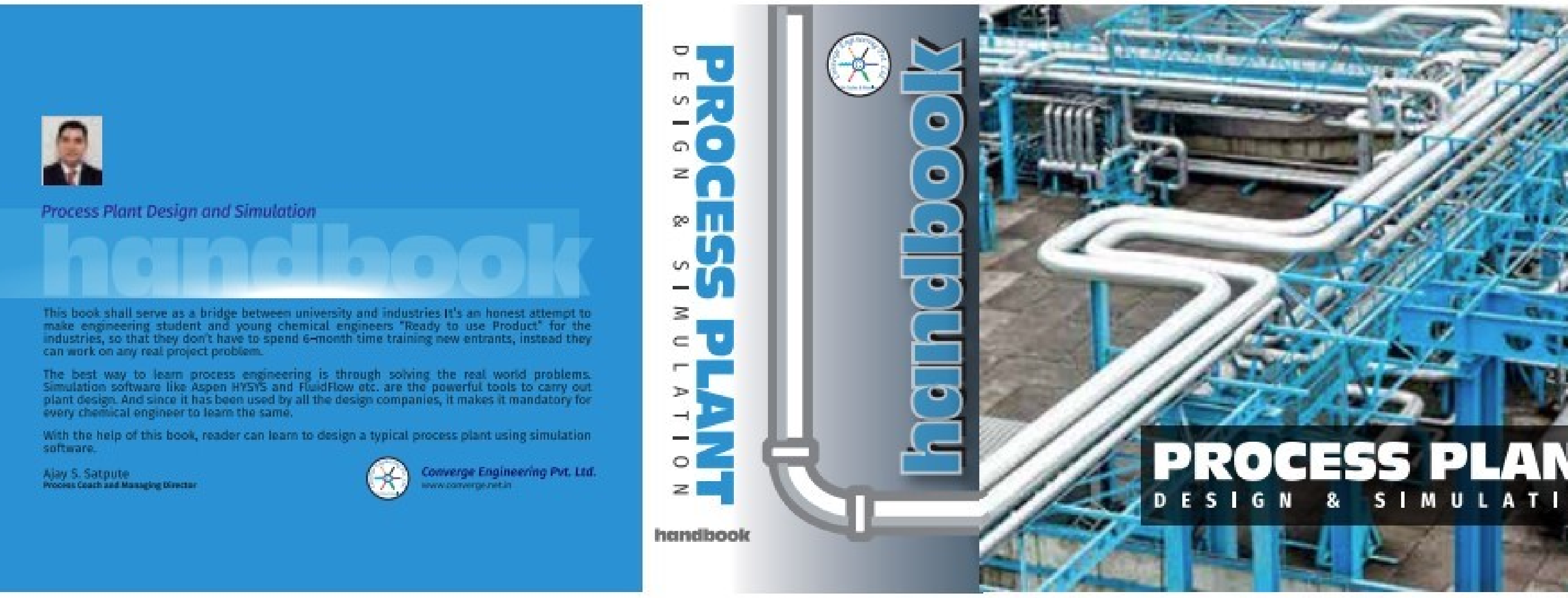

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