Supercritical CO_2 cycles—building the mathematical models

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Co ma być:

1. Założenia teoretyczne dla poszczególnych urządzeń/modeli
2. Print–screeny z hysysa/gate cycla/ebsilona
3. przykladowe wyniki

1 Introduction

The aim of this paper is development of models of main elements of supercritical CO_2 cycles.

2 +Theory

2.1 Heat exchanger

A heat exchanger is a device used to transfer heat between fluids. In supercritical cycles CO_2, there are as many as three points in a supercritical carbon dioxide cycle where a process of heat exchange is employed (heat input, heat rejection and recuperation), hence heat exchangers play a critical role in the cycle design.

In general a heat exchanger is characterized by two types of losses. First, there are losses associated with the heat transfer across the fluid-to-fluid temperature difference, ΔT. These losses are due to a finite exchanger heat-transfer area. The magnitude of temperature difference losses is usually assessed by using a concept of effectiveness defined as:

$$\epsilon_R = \frac{Q}{Q_{max}} \tag{1}$$

where the term in the denominator is the absolute maximum heat that can be transferred from a fluid at higher temperature to another fluid at lower temperature. This maximum amount of heat transfer can only occur in a heat exchanger whose area approaches infinity.

Besides the ΔT losses, there are frictional pressure drops ΔP in the exchanger channels. These losses depend on a number of factors, namely the type of flow (laminar or turbulent) and the channels geometry. The total pressure drop is obtained by taking into account all the existing contributions:

$$\Delta p = \Delta p_i + \Delta p_c + \Delta p_a + \Delta p_e \tag{2}$$

where: Δp_i - entrance loss; Δp_c - core loss (friction term); Δp_a - core loss (acceleration/decelaration term); Δp_e - exit loss [**?**].

Specifications

Line connections	
1	Primary side inlet (cold stream, inside tubes)
2	Primary side outlet (cold stream, inside tubes)
3	Secondary side inlet (hot stream, outside tubes)
4	Secondary side outlet (hot stream, outside tubes)
5	(K*F)-controlling inlet

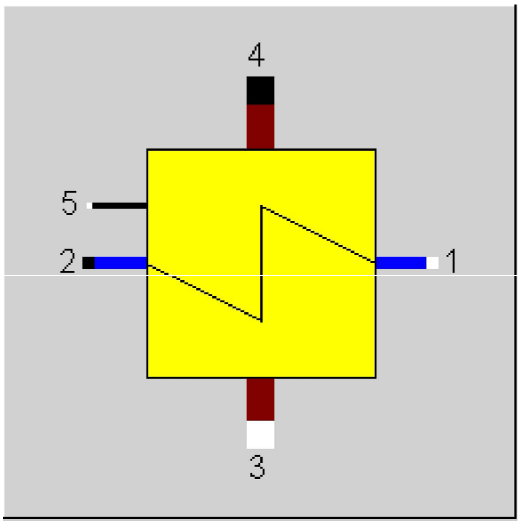


Figure 1: Specifications for a model of heat exchanger in the used software

Pressure losses generally increase with increasing the heat transfer area. Therefore, the ΔT and ΔP losses are said to be coupled in the sense that any design change aimed at reducing one type of loss is likely to have an opposite effect on the other. Due to this coupling it is often difficult to determine *apriori* whether a proposed design modification will yield a net improvement in heat exchanger performance [**?**].

The model of heat exchanger is shown in Fig. 1, the model contains four connections: inlet and outlet streams for two sides of the heat exhangers and additionally a controlling connection.

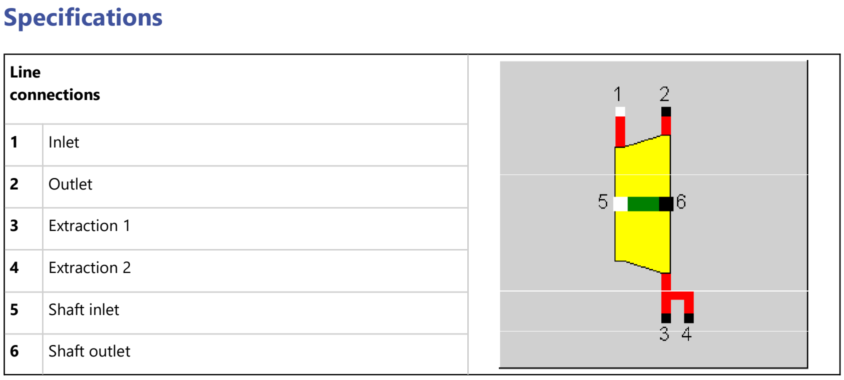
2.2 Expander

In general, a turbine is defined as a rotary device that extracts energy from a fluid flow and converts it into mechanical power. It is assumed that expansion process, which happens during the turbine work, is an adiabatic but not isentropic process. Thus, the definition of efficiency has to be introduced:

$$\eta_T = \frac{h_3 - h_4}{h_{3,s} - h_4} = \frac{\Delta h}{\Delta h_s} \tag{3}$$

where letters denoted by index s stand for ideal values that would occur in the isentropic expansion process. h_3 and h_4 are specific enthalpy values before and after the turbine respectively. Reduced turbine efficiency reduces the thermal efficiency of a cycle and the total work output. However, turbine imperfections are not so detrimental to the total cycle work output as those of a compressor, since the heat produced in dissipation process is transferred to working fluid and thus can be utilized by next turbine stages.

Component General Expander (see Fig. 2) serves the purpose of converting thermal/potential energy of a process vapour into mechanical energy to a shaft. It can be applied to water (incompressible flow, hydraulic turbine), to steam or any other gases as defined by stream type Gas, Fluegas, Universial Fluid, and 2-phase vapor/liquid (compressible flow, turbo machinery). As such it is a most versatile component in EBSILON to model energy conversion by means of expansion



Specifications

Line connections	
1	Inlet
2	Outlet
3	Extraction 1
4	Extraction 2
5	Shaft inlet
6	Shaft outlet

Figure 2: A view of the model topological icon of expander in the used software

of a process stream. Component General Expander represents a single expansion stage, a stage group, or a complete expansion section of the modeled equipment.

The expander model is shown in Fig. 2, the model has inlet and outlet streams as well as extractions. Two energy streams can be connected to the model.

2.3 Compressor

A compressor is defined as a fluid handling mechanical device capable of efficiently transferring energy to the fluid medium so that it can be delivered at elevated pressure conditions. Compressors are similar to pumps: both increase the pressure of a fluid, however, the compressor also reduces the volume of a gas. Since liquids are not compressible or poorly compressible, there is no substantial change of liquid volume during the pump work.

The work in a compressor under ideal conditions occurs at constant entropy. In the actual process entropy rises. This deviation from the ideal performance can be measured using isentropic efficiency of the compressor defined as:

$$\eta_{C(P)} = \frac{h_{1,s} - h_0}{h_1 - h_0} = \frac{h_s}{h} \tag{4}$$

The isentropic efficiency depends both on external and internal factors. A critical influence on compressor performance has the airfoils design, nevertheless, the fluid medium composition and inlet conditions may also affect the compressor efficiency.

Most Brayton cycle turbomachinery applications deal with working fluids which are near-ideal gases. The supercritical CO_2 cycle compressors operate near critical point, thus a real gas model has to be used.

The model of compressor was implemented in Ebsilon Professional by using the component "compressor". In general, this component is used to simulate the increase the pressure of medium.

As shown in Fig. 3, the model of a compressor requires two material streams (inlet and outlet) and one energy stream (shaft power). In the super critical CO_2 cycles we do not assume any cooling system of the compressor (intersection cooling), thus the model seems to be appropriate for given task.

The selected component requires connection of three streams: inlet gas, outlet gas and shaft (power) as well as it requires definition of isentropic and mechanical efficiency. The list of required input is parameters is displayed in the Fig. 4.

Specifications

Line connections	
1	Inlet
2	Outlet
3	Shaft

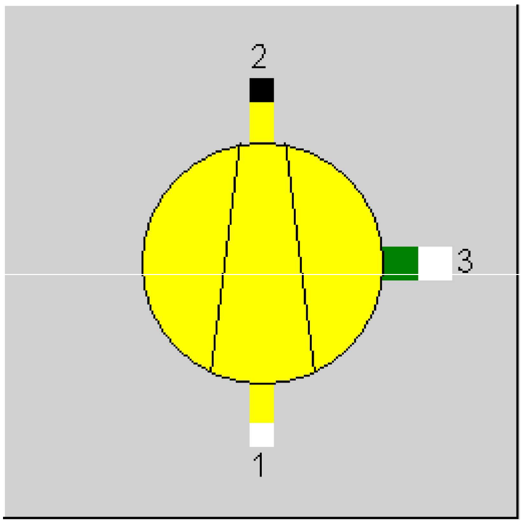


Figure 3: Component compressor

Calculation mode (design / off-design)	FMODE	GLOBAL : 0	
Specification of enthalpies and power	FSPECH	Efficiency charline used : 0	
Validation of isentropic efficiency	FVALETAI	ETAIN used without validation : 0	
Isentropic efficiency (nominal)	ETAIN	0.85	-
Index for pseudo measurement point	IPS		
Usage of ADAPT / EADAPT	FADAPT	Not used and not evaluated : 0	
Adaptation function	EADAPT		
Mechanical efficiency (nominal)	ETAMN	0.99	-
Mechanical loss (constant fraction)	QLOSSM	0	kW
(Deprecated) type of charline	FCHR		
Mass flow (nominal)	M1N	0.3	kg/s

Figure 4: List of required parameters for Ebsilon

Figure 5: CO_2 compressor at Sandia National Laboratories [[Pecnik2011Accurate]]

3 Validation of the used models

3.1 CO_2 compressor

The model of CO_2 compressor is validated with experimental data provided by Sandia National Laboratories [[Pecnik2011Accurate]]. The compressor wheel is shown in Fig. 5.

The image from data acquisition and control system is shown in Fig. 6. It illustrates the T-S diagram of S-$CO_2$where there are plot the state points for one experiment that stepped the shaft speeds from 10,000 rpm to 65,000 rpm. The red dots show the T-S locations at compressor inlet, the compressor outlet (green).

Based on the experimental data from Sandia National Laboratories, the performance map of the compressor was created – Fig. 7. The efficiencies are based on the measured motor controller power with corrections to account for windage losses and pump vane power losses which are estimated to be 17% of the windage losses [[Wright2010sCO2]]. In addition, authors [[Wright2010sCO2]] proposed a model of examined compressor and its performance compared with experimental data, which are displayed in the performance map 7.

Data used for validation are taken from High Speed Spin Test (75000,00 rpm). The compressor performance during this test is displayed in Table 1. The simulation results of compressor, which was tested at Sandia National Laboratiories, is shown in Figure 8.

3.2 CO_2 expander

The model of CO_2 expander is verified with main compressor turbine, which is installed in test loop at Sandia National Laboratories [[2012SandiaReport]]. The examined turbine is operating in split-flow recompression Brayton cycle – denoted as Turb-1 in Fig. 9.

The design of radial turbine wheel (see Fig. 10) were developed by BNI. Its made of Inconel 718

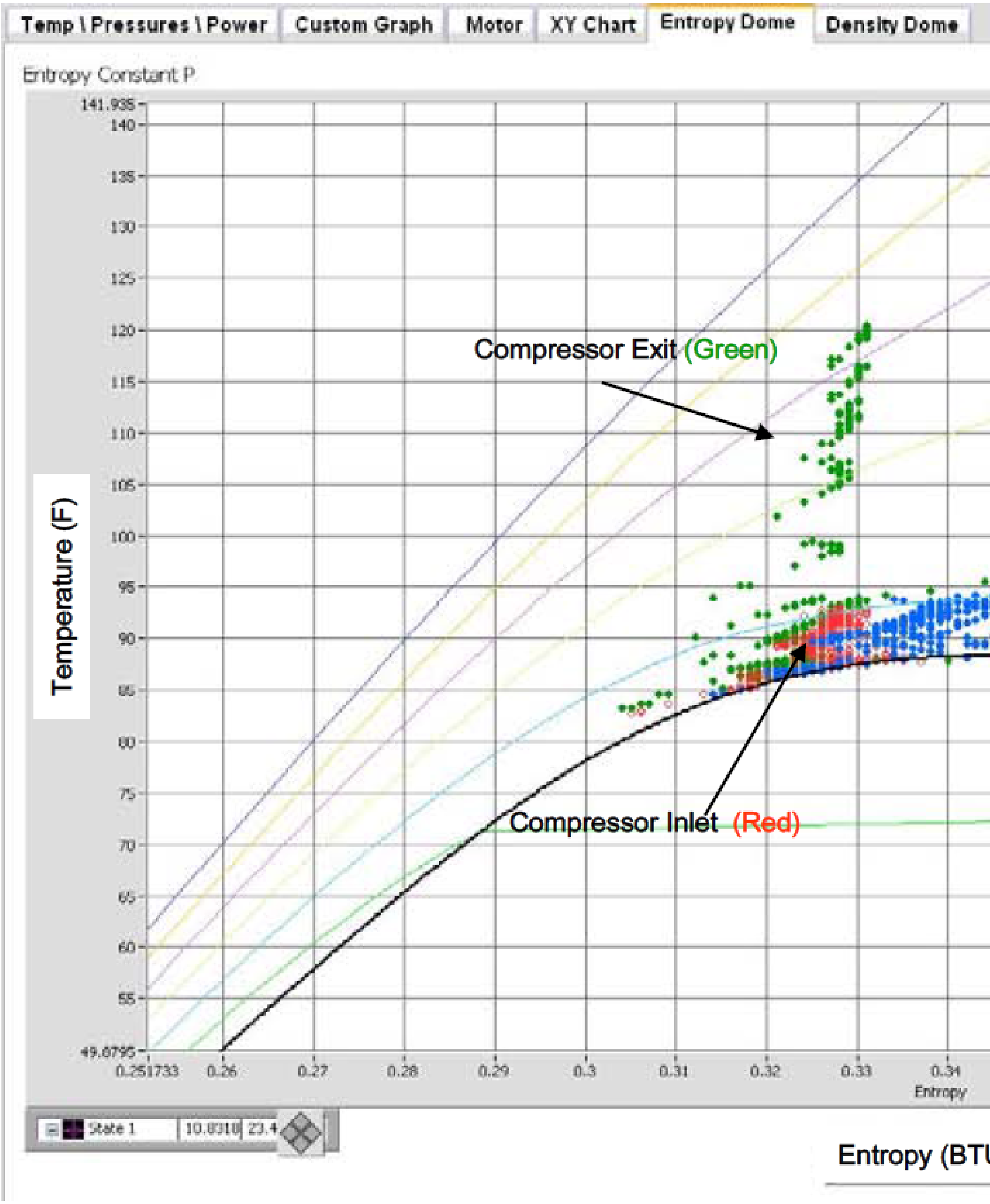


Figure 6: Image from the Sandia S-CO2 compression loop control system showing the location of the state points on the T-S diagram. Red and green points are compressor inlet and outlet conditions (respectively) [[Wright2010sCO2]]

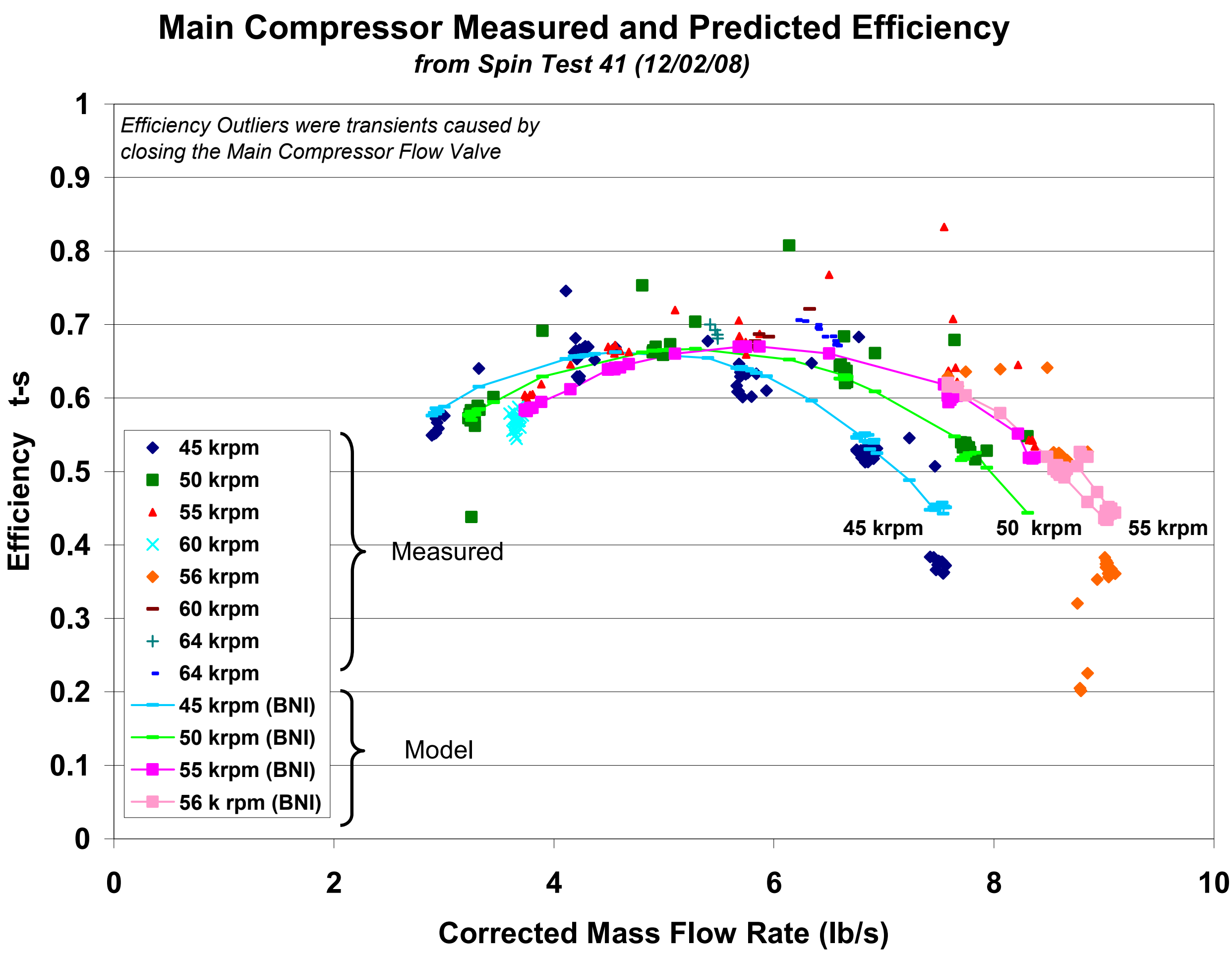


Figure 7: Comparison of the predicted and measured compressor efficiency for the main compressor in the Sandia National Laboratories supercritical CO2 test loop. The plot shows the compressor efficiency (t-s) a function of corrected mass flow rate for parametric variations in corrected speed [[Wright2010sCO2]]

Table 1: Comparison of experimental data and simulation results

	Test data [[Pecnik2011Accurate]]	Validation
Pressure at the inlet, bar	76,90	76,90
Temperature at the inlet, K	305,30	305,3
Pressure at the outlet, bar	139,84	139,84
Temperature at the outlet, K	324,66	324,151
Mass flow. kg.s	3,53	3,53
RPM, rev/min	75000,00	—
Efficiency, %	75,20	75,20

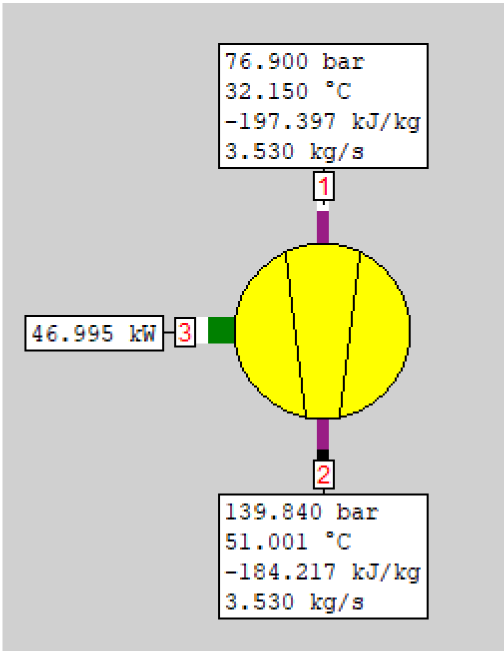


Figure 8: Simulation results of compressor

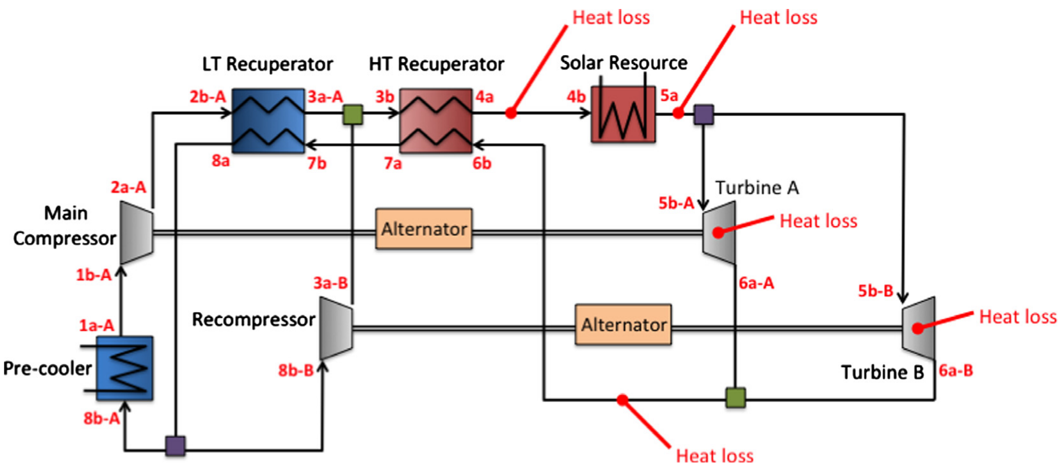


Figure 9: Layout of split-flow recompression Brayton cycle [[2013IversonsCO2]]

Figure 10: Wheel of main compressor turbine

due to its ability to withstand high temperatures and stresses. The turbine performance map is shown in Fig. 11 again with the design point indicated by a red diamond.

Data used for validation are taken main compressor CO_2 turbine, which was tested at Sandia National Laboratories. State points measured at steady operation and calculated values are displayed in Table 2. The simulation results of main compressor turbine, which was tested at Sandia National Laboratiories, is shown in Figure 8.

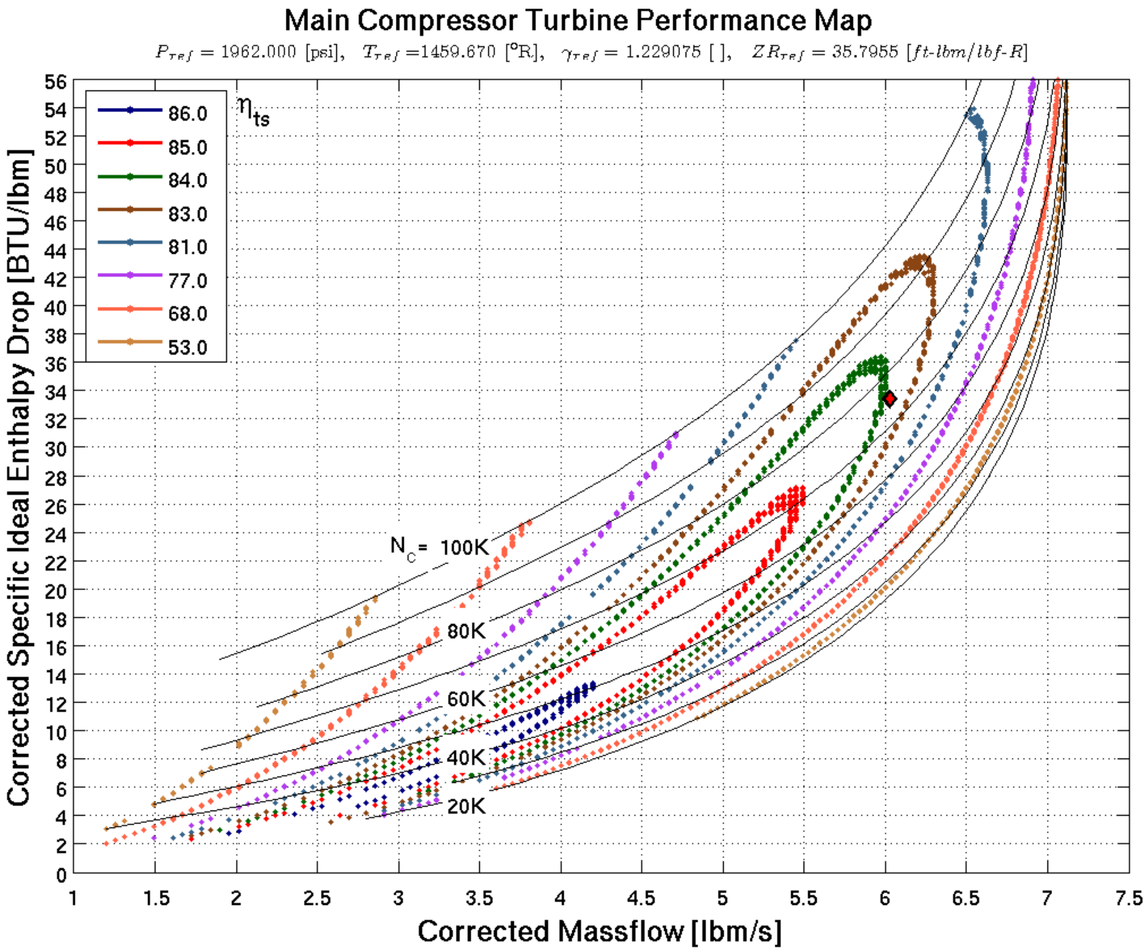


Figure 11: Performance map of main compressor turbine

Table 2: Comparison of experimental data and simulation results

	Test data [[2013IversonsCO2]]	Validation
Pressure at the inlet, kPa	9893.7	9893.7
Temperature at the inlet, C	390	390
Pressure at the outlet, bar	7938.4	7938.4
Temperature at the outlet, C	368.9	367.3
Mass flow. kg.s	1.741	1.741
Efficiency, %	86%	86%

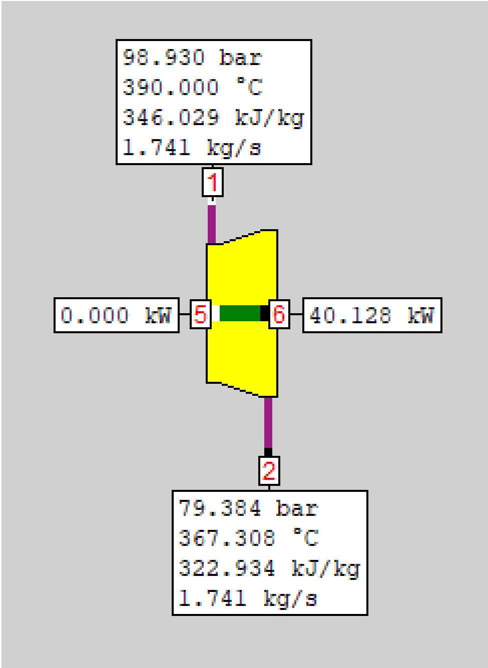


Figure 12: Simulation results of CO_2 expander

4 Discussion

5 Conclusions

Acknowledgments

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