ThermoFluid Studio v0.5.1 — Solver Hand-Verification Document

Independent state-by-state verification of 15 thermo-fluid systems against CoolProp

ThermoFluid Studio verification harness (`docs/verification/`)

2026-07-19

Abstract

15 systems spanning power cycles, refrigeration, gas turbines, hydraulics, and combined plants — from 3 to 9 components — were solved in ThermoFluid Studio and re-derived by hand from CoolProp property data. 266 of 266 individual comparisons pass, all at machine precision. Three real defects surfaced by early runs of this campaign (§2) were fixed in v0.5.1 and are covered by new regression tests; the results printed here are from the fixed build.

Verified systems

ID	System	Category	Fluid	Comp.	Checks
T1	Ideal Rankine cycle (Water)	thermo	Water	4	22/22
T2	Superheated Rankine with component losses (Water)	thermo	Water	4	18/18
T3	Reheat Rankine cycle (Water)	thermo	Water	6	19/19
T4	Regenerative Rankine with open feedwater heater (Water)	thermo	Water	8	33/33
T5	Vapor-compression refrigeration (R134a)	thermo	R134a	4	17/17
T6	VCR with suction-line heat exchanger (R134a)	thermo	R134a	6	18/18
T7	Recuperated closed Brayton cycle (Helium)	thermo	Helium	5	19/19
T8	Open Brayton cycle (Air)	thermo	Air	5	17/17
T9	Transcritical CO2 heat pump with JT throttle	thermo	CO2	4	15/15
F1	Pumped water transfer line (turbulent Darcy-Weisbach)	fluids	Water	6	18/18
F2	Laminar micro-flow line (f = 64/Re)	fluids	Water	3	9/9
F3	Pumped riser and downcomer (elevation head)	fluids	Water	5	12/12
F4	Steam nozzle and diffuser train	fluids	Water	4	9/9
C1	Steam plant with real piping (combo)	combo	Water	6	18/18
C2	Two-loop project: Rankine + VCR side by side	combo	Water+R134a	8	22/22

1 Purpose and method

This document is the hand-verification record for the ThermoFluid Studio network solver. Every system below was built through the application's own project model, solved by the shipping `NetworkSolver`, and then *independently* re-derived by hand: each state is marched from its inlet using the component governing equations and property lookups made directly against CoolProp 8.0 (`PropsSI`), bypassing all of the application's property and solver code. The hand transcript printed with each system is the actual calculation, with the actual numbers.

Governing equations used in the hand calculations

Component	Outlet-enthalpy relation
Turbine / Nozzle	$h_{out} = h_{in} - \eta\left(h_{in} - h(P_{out}, s_{in})\right)$
Pump / Compressor / Diffuser	$h_{out} = h_{in} + \big(h(P_{out}, s_{in}) - h_{in}\big)/\eta$
Throttle	$h_{out} = h_{in}$ (isenthalpic)
Boiler / Heater / Evaporator	$h(P_{out}, T_{set})$, or $h_{in} + \eta_{th}\dot{Q}/\dot{m}$, or $h(P_{out}, x_{set})$
Condenser / Cooler	$h(P_{out}, T_{set})$, or $h_{in} - \dot{Q}/\dot{m}$, or $h(P_{out}, x_{set})$
Recuperator	$q = \varepsilon\ \min\big(q_{max,hot},\ q_{max,cold}\big)$, see §2
Mixer / Splitter	mass and energy conservation; splitter imposes the flow fraction
Pipe	$\Delta P = \big(fL/D + \Sigma K\big)\frac{1}{2}\rho V^2 + \rho g \Delta z$; $\quad h_{out} = h_{in} - \dot{Q}_{loss}/\dot{m} - g\Delta z$
Bend	$\Delta P = K\frac{1}{2}\rho V^2$, K specified or $f \cdot (L_e/D)$ (Crane TP-410)
Friction factor	$f = 64/\mathrm{Re}$ (laminar, $\mathrm{Re} < 2300$); Swamee–Jain $f = 0.25\big/\log_{10}\!\big(\frac{\epsilon}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\big)^2$

Units throughout: kPa, °C, kJ/kg, kJ/(kg K), kg/s, kW.

Acceptance tolerances

A check passes when either bound holds: pressure 0.1 kPa or 0.02%; temperature 0.05 K; enthalpy 0.1 kJ/kg or 0.02%; entropy 0.002 kJ/(kg K); mass flow 10^{-6} kg/s; quality 5×10^{-4}; cycle energy quantities 0.5 kW or 0.2%. The solver's own convergence tolerances sit orders of magnitude inside these, so a failure is a real disagreement, not numerical noise.

2 Defects found by this campaign, and their fixes

Three real product defects were found by these hand checks and fixed in v0.5.1; all systems below were re-verified after the fixes.

1. **Recuperator could move heat from cold to hot (second-law violation).** The effectiveness model used $q = \varepsilon\,\dot{m}_{min}(h_{hot,in} - h_{cold,in})$, which is only valid when both streams are comparable single-phase gases. In two-phase service — e.g. a suction-line heat exchanger, warm liquid against cold vapor — latent heat makes the cold vapor's *enthalpy* exceed the warm liquid's, the bracket goes negative, and the solver happily heated the 46 °C liquid with −10 °C vapor (System T6 caught this: 105 kJ/kg moved the wrong way). The model now uses the standard generalization $q_{max,hot} = \dot{m}_h\big(h_{h,in} - h(P_{h,out}, T_{c,in})\big)$, $q_{max,cold} = \dot{m}_c\big(h(P_{c,out}, T_{h,in}) - h_{c,in}\big)$,

$q = \varepsilon \max\big(0, \min(q_{max,hot}, q_{max,cold})\big)$, which is exact for the ideal-gas case the old formula targeted and stays physical through phase change.

2. **Recuperator duty polluted the cycle summary.** The internal recuperator transfer was summed into `heat_rejected_kW`, so $\dot{Q}_{in} - \dot{Q}_{rej} \neq \dot{W}_{net}$ for every recuperated cycle (System T7: 539 kW of internal transfer reported as plant heat rejection). Recuperators are now excluded from the external heat totals; first-law closure of the summary is restored and regression-tested.

3. **Pipe ambient heat loss vanished from the summary.** A pipe's `heat_loss_kW` correctly lowered the stream enthalpy but was never reported as component heat, so it was missing from `heat_rejected_kW` (System C1: 45 kW pipe loss broke first-law closure by exactly 45 kW). Pipe losses now count as heat rejection.

New in v0.5.1: pipe elevation change ($\rho g \Delta z$)

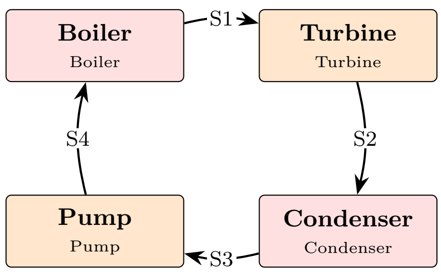
Added with this campaign: a Pipe now takes an *elevation change* Δz (outlet minus inlet, in m). The pressure balance gains the static head $\rho g \Delta z$ — signed, so a riser loses pressure and a downcomer recovers it — and the energy balance gains the potential-energy term $g\Delta z$ (kJ/kg). It applies in both the specified-drop and Darcy–Weisbach pressure models and is verified by hand in System F3.

3 [T1] Ideal Rankine cycle (Water)

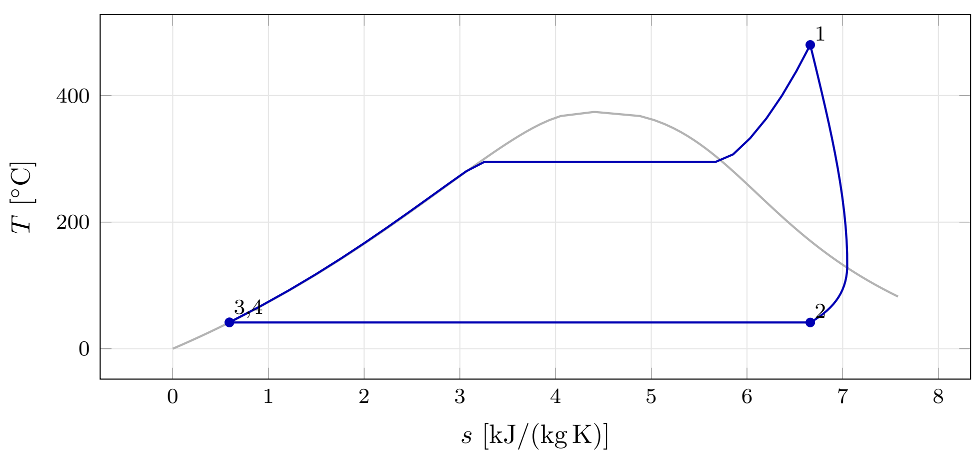
4-component ideal Rankine: isentropic turbine and pump (eta=1), no pressure drops, saturated-liquid condenser. 8 MPa boiler / 8 kPa condenser, 480 °C throttle temperature, mdot = 1.2 kg/s.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (Water)



Reading the diagram — coincident states. This is physics, not a plotting error. States 3, 4 coincide at plot scale (ΔT = 0.24 K, Δs = 0.0000 kJ/(kg K), ΔP = 7992 kPa, Δh = 8.05 kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other.

Hand calculation

- State 1 (boiler out): P1 = 8000 kPa, T1 = 480 C → h1 = 3349.645 kJ/kg, s1 = 6.66126 kJ/kg-K
- State 2 (turbine out): isentropic to P2 = 8 kPa: h2 = h(P2, s1) = 2083.432 kJ/kg, x2 = 0.7949
- State 3 (condenser out): saturated liquid at 8 kPa: h3 = 173.840 kJ/kg, T3 = 41.509 C
- State 4 (pump out): isentropic to 8000 kPa: h4 = h(P4, s3) = 181.886 kJ/kg
- Qin = m(h1-h4) = 3801.31 kW; Qrej = m(h2-h3) = 2291.51 kW; Wt = 1519.46 kW; Wp = 9.66 kW; eta = 0.39718

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	8000	8000	0	OK
State 1	T_C	480	480	0	OK
State 1	h_kJ_kg	3349.65	3349.65	0	OK
State 1	s_kJ_kgK	6.66126	6.66126	0	OK
State 1	mdot_kg_s	1.2	1.2	0	OK
State 2	P_kPa	8	8	0	OK
State 2	h_kJ_kg	2083.43	2083.43	0	OK
State 2	x	0.79488	0.79488	0	OK
State 2	T_C	41.5088	41.5088	0	OK
State 3	P_kPa	8	8	0	OK
State 3	h_kJ_kg	173.84	173.84	0	OK
State 3	x	0	0	0	OK
State 4	P_kPa	8000	8000	0	OK
State 4	h_kJ_kg	181.886	181.886	0	OK
State 4	T_C	41.7509	41.7509	0	OK

Cycle summary comparison

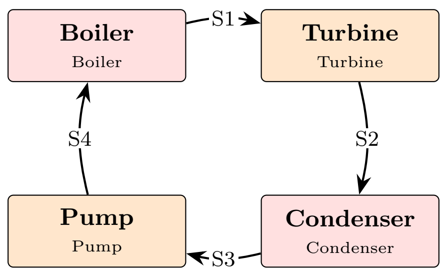
Cycle quantity	Hand	Software	Diff	Status
heat_input_kW	3801.31	3801.31	0	OK
heat_rejected_kW	2291.51	2291.51	0	OK
gross_work_kW	1519.46	1519.46	0	OK
parasitic_work_kW	9.65526	9.65526	0	OK
net_work_kW	1509.8	1509.8	0	OK
thermal_efficiency	0.397179	0.397179	0	OK
first_law_closure_kW	1509.8	1509.8	0	OK

4 [T2] Superheated Rankine with component losses (Water)

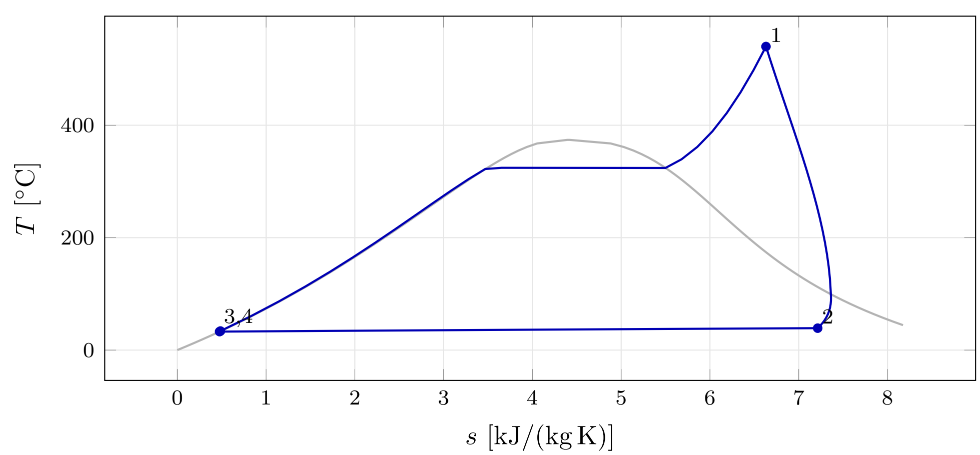
4-component Rankine with real machines: eta_t = 0.87, eta_p = 0.80, boiler dP = 150 kPa, condenser dP = 2 kPa. Pump to 12 MPa, 540 °C throttle, 7 kPa exhaust, mdot = 35 kg/s (approx. 40 MW plant).

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (Water)



Reading the diagram — coincident states. This is physics, not a plotting error. States 3, 4 coincide at plot scale ($\Delta T = 1.02$ K, $\Delta s = 0.0098$ kJ/(kg K), $\Delta P = 11995$ kPa, $\Delta h = 15.03$ kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other.

Hand calculation

- State 1: P1 = 12000 - 150 = 11850 kPa, T1 = 540 C → h1 = 3457.372, s1 = 6.63103
- State 2: h2s = h(7 kPa, s1) = 2058.723; h2 = h1 - 0.87(h1 - h2s) = 2240.548; x2 = 0.8625
- State 3: P3 = 7 - 2 = 5 kPa sat liquid: h3 = 137.749, T3 = 32.874 C
- State 4: h4s = h(12 MPa, s3) = 149.776; h4 = h3 + (h4s - h3)/0.80 = 152.783
- Qin = 115660.6 kW; Qrej = 73598.0 kW; Wt = 42588.9 kW; Wp = 526.2 kW; eta = 0.36367

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P__kPa	11850	11850	0	OK
State 1	T__C	540	540	-5.68434e-13	OK
State 1	h__kJ__kg	3457.37	3457.37	0	OK
State 1	s__kJ__kgK	6.63103	6.63103	-3.55271e-15	OK
State 1	mdot__kg__s	35	35	0	OK
State 2	P__kPa	7	7	0	OK
State 2	h__kJ__kg	2240.55	2240.55	-9.09495e-13	OK
State 2	x	0.862491	0.862491	-3.33067e-16	OK
State 3	P__kPa	5	5	0	OK
State 3	h__kJ__kg	137.749	137.749	0	OK
State 3	x	0	0	0	OK
State 4	P__kPa	12000	12000	0	OK
State 4	h__kJ__kg	152.783	152.783	0	OK
State 4	T__C	33.8935	33.8935	0	OK

Cycle summary comparison

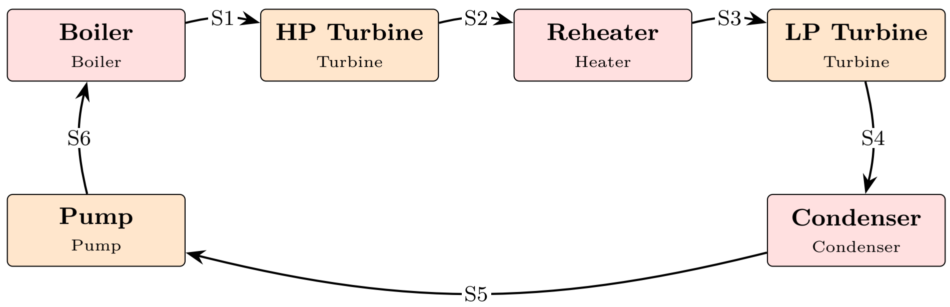
Cycle quantity	Hand	Software	Diff	Status
heat__input__kW	115661	115661	0	OK
heat__rejected__kW	73598	73598	-2.91038e-11	OK
net__work__kW	42062.7	42062.7	2.91038e-11	OK
thermal__efficiency	0.363673	0.363673	2.22045e-16	OK

5 [T3] Reheat Rankine cycle (Water)

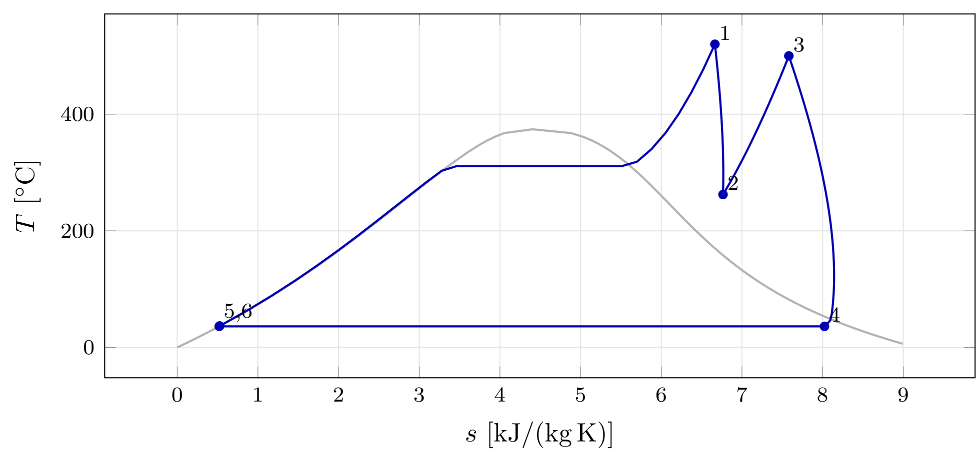
6-component reheat Rankine: HP turbine to 1.5 MPa, reheat to 500 °C (30 kPa reheater dP), LP turbine to 6 kPa. 10 MPa boiler, 520 °C, mdot = 15 kg/s.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (Water)



Reading the diagram — coincident states. This is physics, not a plotting error. States 5, 6 coincide at plot scale ($\Delta T = 0.69$ K, $\Delta s = 0.0057$ kJ/(kg K), $\Delta P = 9994$ kPa, $\Delta h = 11.81$ kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other.

Hand calculation

- State 1: 10 MPa, 520 C → h1 = 3426.368, s1 = 6.66491
- State 2 (HP exit): h2s = 2899.996; h2 = h1 - 0.90(h1-h2s) = 2952.633; s2 = 6.76533
- State 3 (reheat exit): P3 = 1470 kPa, 500 C → h3 = 3474.017, s3 = 7.58142
- State 4 (LP exit): h4s = 2335.384; h4 = 2472.020; x4 = 0.9608
- State 5: sat liquid 6 kPa: h5 = 151.478

- State 6 (pump out): h6 = h5 + (h6s - h5)/0.85 = 163.286
- Qin = m(h1-h6) + m(h3-h2) = 56767.0 kW; Wgross = 22136.0 kW; Wpump = 177.1 kW; eta = 0.38682

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	10000	10000	0	OK
State 1	h_kJ_kg	3426.37	3426.37	0	OK
State 1	s_kJ_kgK	6.66491	6.66491	0	OK
State 1	mdot_kg_s	15	15	0	OK
State 2	P_kPa	1500	1500	0	OK
State 2	h_kJ_kg	2952.63	2952.63	0	OK
State 3	P_kPa	1470	1470	0	OK
State 3	h_kJ_kg	3474.02	3474.02	0	OK
State 4	P_kPa	6	6	0	OK
State 4	h_kJ_kg	2472.02	2472.02	-1.3506e-10	OK
State 4	x	0.960827	0.960827	-5.59552e-14	OK
State 5	P_kPa	6	6	0	OK
State 5	h_kJ_kg	151.478	151.478	0	OK
State 6	P_kPa	10000	10000	0	OK
State 6	h_kJ_kg	163.286	163.286	0	OK

Cycle summary comparison

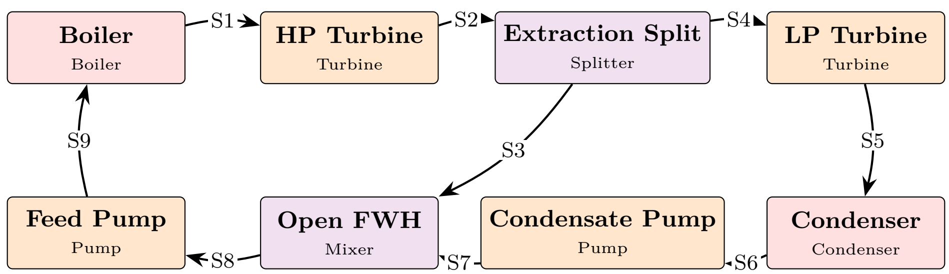
Cycle quantity	Hand	Software	Diff	Status
heat_input_kW	56767	56767	0	OK
gross_work_kW	22136	22136	2.02635e-09	OK
net_work_kW	21958.9	21958.9	2.02635e-09	OK
thermal_efficiency	0.386824	0.386824	3.56937e-14	OK

6 [T4] Regenerative Rankine with open feedwater heater (Water)

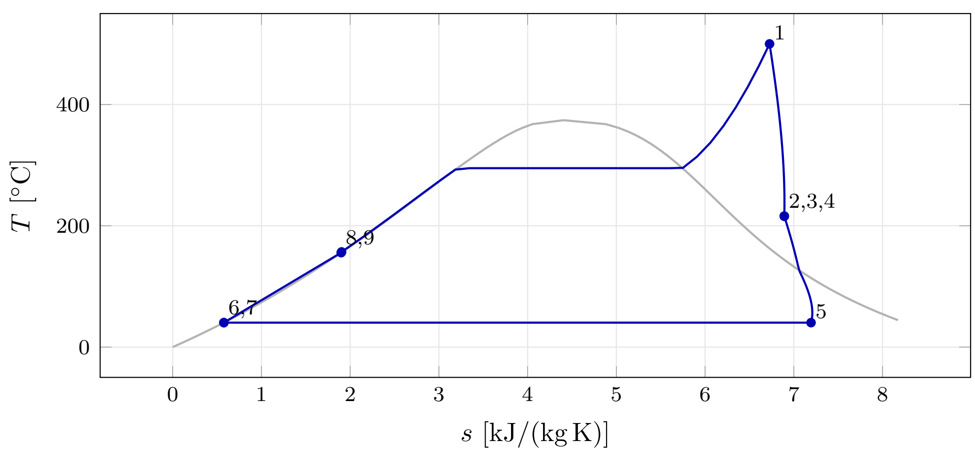
8-component regenerative Rankine: 18% extraction at 0.8 MPa to an open FWH (Mixer), condensate pump to 0.8 MPa, feed pump to 8 MPa. Exercises Splitter mass fractions and Mixer energy balance. mdot = 20 kg/s.

Solver status: Fully constrained, residual RMS = 1.33e-17.

System diagram



T–s diagram, process paths traced (Water)



Reading the diagram — coincident states. This is physics, not a plotting error. States 2, 3, 4 coincide at plot scale ($\Delta T = 0.00$ K, $\Delta s = 0.0000$ kJ/(kg K), $\Delta P = 0$ kPa, $\Delta h = 0.00$ kJ/kg): a junction (splitter) duplicates the thermodynamic state - only the mass flows differ. States 6, 7 coincide at plot scale ($\Delta T = 0.07$ K, $\Delta s = 0.0006$ kJ/(kg K), $\Delta P = 792$ kPa, $\Delta h = 1.00$ kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other. States 8, 9 coincide at plot scale ($\Delta T = 1.28$ K, $\Delta s = 0.0046$ kJ/(kg K), $\Delta P = 7200$ kPa, $\Delta h = 9.85$ kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other.

Hand calculation

- State 1: 8 MPa, 500 C → h1 = 3399.492, s1 = 6.72659; mdot = 20 kg/s
- State 2: h2 = h1 - 0.87(h1 - h(0.8 MPa, s1)) = 2875.755

- States 3/4 (splitter): h unchanged = 2875.755; m3 = 0.18*20 = 3.60, m4 = 16.40 kg/s
- State 5 (LP exit): s2 = 6.89249; h5 = h2 - 0.87(h2 - h(7.5 kPa, s2)) = 2243.047; x5 = 0.8624
- State 6: sat liquid 7.5 kPa: h6 = 168.746
- State 7 (condensate pump out): h7 = 169.745
- State 8 (FWH out): h8 = (16.4*h7 + 3.6*h3)/20 = 656.827 at 0.8 MPa
- State 9 (feed pump out): h9 = h8 + (h(8 MPa, s8) - h8)/0.80 = 666.679
- Qin = 54656.2 kW; Wgross = 20851.1 kW; Wpumps = 213.42 kW; Qrej = 34018.5 kW; eta = 0.37759

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	8000	8000	0	OK
State 1	h_kJ_kg	3399.49	3399.49	0	OK
State 1	mdot_kg_s	20	20	0	OK
State 2	P_kPa	800	800	0	OK
State 2	h_kJ_kg	2875.76	2875.76	0	OK
State 2	mdot_kg_s	20	20	0	OK
State 3	P_kPa	800	800	0	OK
State 3	h_kJ_kg	2875.76	2875.76	0	OK
State 3	mdot_kg_s	3.6	3.6	-4.44089e-16	OK
State 4	P_kPa	800	800	0	OK
State 4	h_kJ_kg	2875.76	2875.76	0	OK
State 4	mdot_kg_s	16.4	16.4	0	OK
State 5	P_kPa	7.5	7.5	0	OK
State 5	h_kJ_kg	2243.05	2243.05	0	OK
State 5	mdot_kg_s	16.4	16.4	0	OK
State 5	x	0.862394	0.862394	0	OK
State 6	P_kPa	7.5	7.5	0	OK
State 6	h_kJ_kg	168.746	168.746	0	OK
State 6	mdot_kg_s	16.4	16.4	0	OK
State 7	P_kPa	800	800	0	OK
State 7	h_kJ_kg	169.745	169.745	0	OK
State 7	mdot_kg_s	16.4	16.4	0	OK
State 8	P_kPa	800	800	0	OK
State 8	h_kJ_kg	656.827	656.827	0	OK
State 8	mdot_kg_s	20	20	0	OK
State 9	P_kPa	8000	8000	0	OK
State 9	h_kJ_kg	666.679	666.679	0	OK
State 9	mdot_kg_s	20	20	0	OK

Cycle summary comparison

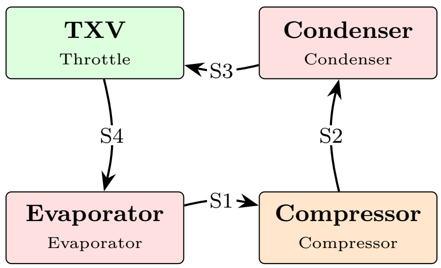
Cycle quantity	Hand	Software	Diff	Status
heat_input_kW	54656.2	54656.2	0	OK
gross_work_kW	20851.1	20851.1	0	OK
parasitic_work_kW	213.423	213.423	0	OK
heat_rejected_kW	34018.5	34018.5	0	OK
thermal_efficiency	0.377591	0.377591	0	OK

7 [T5] Vapor-compression refrigeration (R134a)

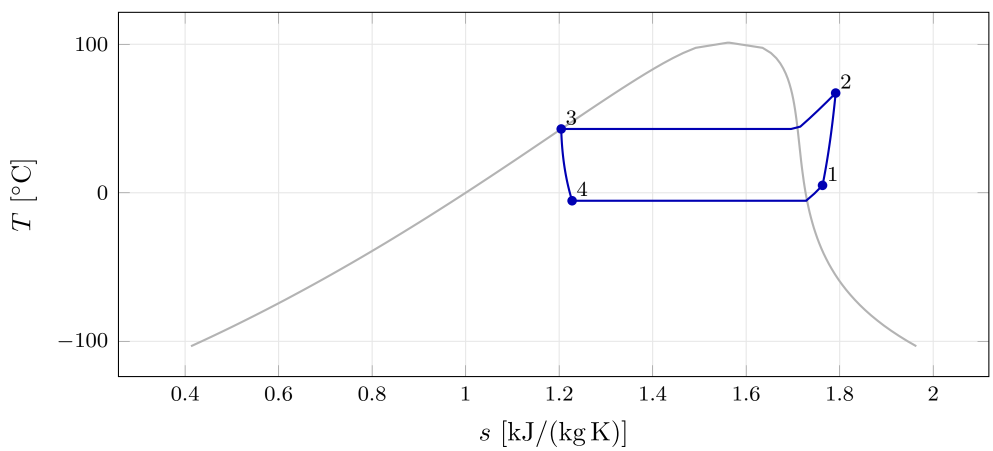
4-component VCR: 240 kPa evaporator with outlet at 5 °C (superheat), compressor to 1100 kPa at eta = 0.78, saturated-liquid condenser, isenthalpic TXV. mdot = 0.045 kg/s.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (R134a)



Hand calculation

- State 1 (evap out): 240 kPa (Tsat = -5.37 C), 5 C → h1 = 404.452, s1 = 1.76328
- State 2: h2s = 437.937; h2 = h1 + (h2s - h1)/0.78 = 447.381; T2 = 67.15 C
- State 3: sat liquid 1100 kPa (Tsat = 42.97 C): h3 = 260.867
- State 4 (TXV out): h4 = h3 = 260.867 at 240 kPa → x4 = 0.3358, T4 = -5.37 C
- Qevap = 6.461 kW; Wcomp = 1.932 kW; Qcond = 8.393 kW; COP = 3.3448

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	240	240	0	OK

State 1	T__C	5	5	2.81943e-11	OK
State 1	h__kJ__kg	404.452	404.452	0	OK
State 1	mdot__kg__s	0.045	0.045	0	OK
State 2	P__kPa	1100	1100	0	OK
State 2	h__kJ__kg	447.381	447.381	3.72324e-11	OK
State 2	T__C	67.1546	67.1546	3.49019e-11	OK
State 3	P__kPa	1100	1100	0	OK
State 3	h__kJ__kg	260.867	260.867	0	OK
State 3	x	0	0	0	OK
State 4	P__kPa	240	240	0	OK
State 4	h__kJ__kg	260.867	260.867	0	OK
State 4	x	0.335797	0.335797	0	OK

Cycle summary comparison

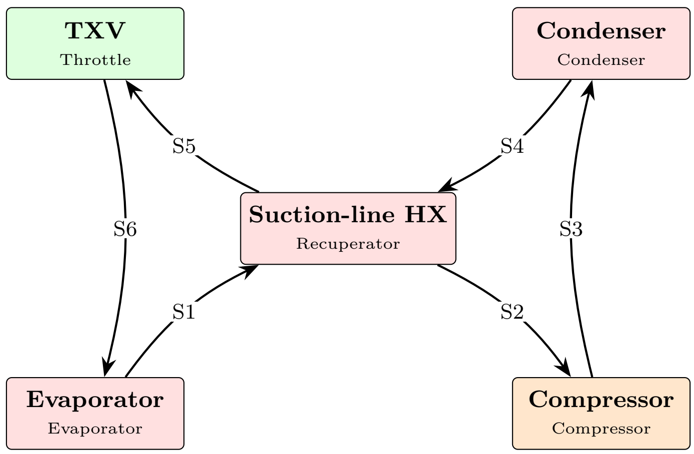
Cycle quantity	Hand	Software	Diff	Status
heat__input__kW	6.46136	6.46136	0	OK
parasitic__work__kW	1.93178	1.93178	1.67555e-12	OK
heat__rejected__kW	8.39315	8.39315	1.6751e-12	OK
refrigeration__COP	3.34477	3.34477	-2.90123e-12	OK

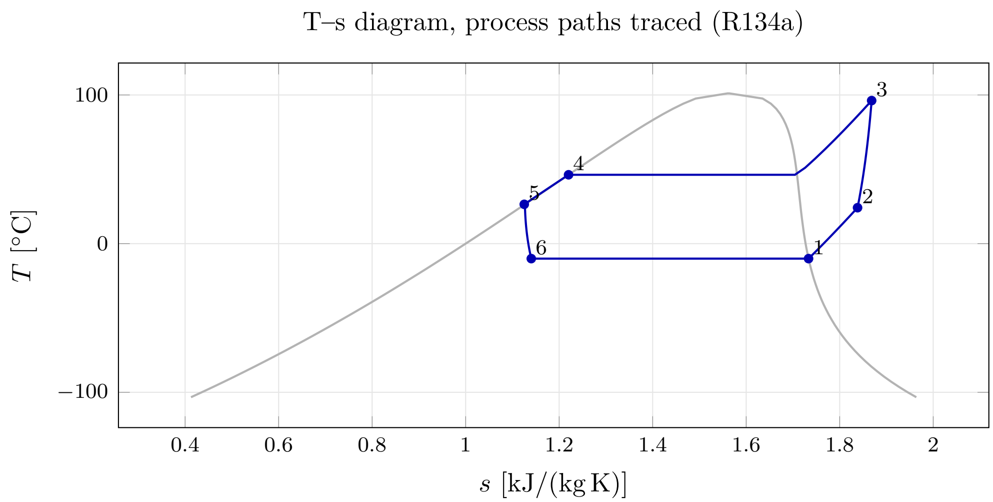
8 [T6] VCR with suction-line heat exchanger (R134a)

6-component VCR with a Recuperator as suction-line HX: condenser liquid subcools against evaporator suction vapor (effectiveness 0.6). 200 kPa / 1200 kPa, mdot = 0.05 kg/s. Physical requirement: heat must flow hot liquid → cold vapor (liquid subcools, vapor superheats).

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram





Hand calculation

- State 1 (evap out): sat vapor 200 kPa: h1 = 392.619, T1 = -10.08 C
- State 4 (cond out): sat liquid 1200 kPa: h4 = 265.947, T4 = 46.31 C
- q_max,hot = m(h4 - h(P_hi, T_cold_in)) = 3.9536 kW; q_max,cold = m(h(P_lo, T_hot_in) - h1) = 2.4445 kW; q = 0.6 * min = 1.4667 kW (must be > 0: hot liquid subcools)
- State 2 (suction, superheated): h2 = h1 + q/m = 421.953, T2 = 24.18 C
- State 5 (subcooled liquid): h5 = h4 - q/m = 236.613, T5 = 26.44 C

- State 3 (compressor out): h3 = 476.849
- State 6 (TXV out): h6 = h5 = 236.613, x6 = 0.2428
- Qevap = 7.8003 kW; Wcomp = 2.7448 kW; COP = 2.8418

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	200	200	0	OK
State 1	h_kJ_kg	392.619	392.619	0	OK
State 1	mdot_kg_s	0.05	0.05	0	OK
State 2	P_kPa	200	200	0	OK
State 2	h_kJ_kg	421.953	421.953	0	OK
State 3	P_kPa	1200	1200	0	OK
State 3	h_kJ_kg	476.849	476.849	0	OK
State 4	P_kPa	1200	1200	0	OK
State 4	h_kJ_kg	265.947	265.947	0	OK
State 4	x	0	0	0	OK
State 5	P_kPa	1200	1200	0	OK
State 5	h_kJ_kg	236.613	236.613	0	OK
State 6	P_kPa	200	200	0	OK
State 6	h_kJ_kg	236.613	236.613	0	OK
State 6	x	0.242776	0.242776	0	OK

Cycle summary comparison

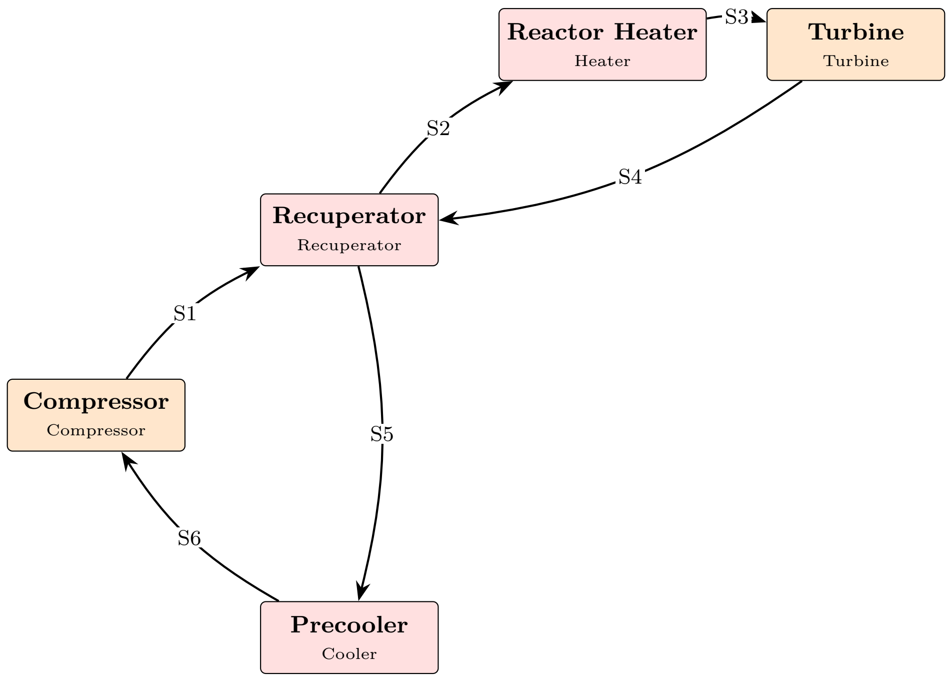
Cycle quantity	Hand	Software	Diff	Status
heat_input_kW	7.80028	7.80028	0	OK
parasitic_work_kW	2.74482	2.74482	0	OK
refrigeration_COP	2.84182	2.84182	0	OK

9 [T7] Recuperated closed Brayton cycle (Helium)

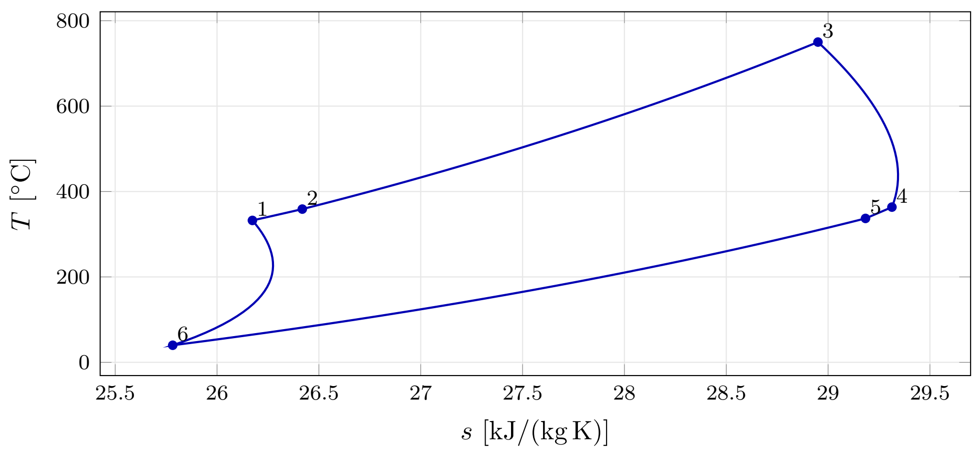
5-component closed helium Brayton with recuperator (effectiveness 0.85): compressor 325 → 1400 kPa at eta = 0.85, heater to 750 °C, turbine to 350 kPa at eta = 0.90, cooler to 40 °C. mdot = 4 kg/s.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (Helium)



Hand calculation

- State 6 (compressor in): P = 350 - 15 - 10 = 325 kPa, 40 C → h6 = 1632.35, s6 = 25.78236

- State 1 (comp out): h1s = 2925.64; h1 = h6 + (h1s - h6)/0.85 = 3153.87, T1 = 332.34 C
- State 3 (heater out): P3 = 1400 - 15 - 20 = 1365 kPa, 750 C → h3 = 5322.43
- State 4 (turbine out): h4s = 3089.22; h4 = h3 - 0.90(h3 - h4s) = 3312.54, T4 = 363.53 C
- Recuperator: q_max,hot = m(h4 - h(335 kPa, T1=332.34 C)) = 648.13 kW; q_max,cold = m(h(1385 kPa, T4=363.53 C) - h1) = 647.67 kW; q = 0.85 * min = 550.52 kW
- State 2 (cold out): h2 = h1 + q/m = 3291.50, T2 = 358.85 C
- State 5 (hot out): h5 = h4 - q/m = 3174.91, T5 = 337.04 C
- Qin = m(h3 - h2) = 8123.7 kW; Wturb = 8039.6 kW; Wcomp = 6086.1 kW; Qrej(precooler) = m(h5 - h6) = 6170.2 kW
- First law: Qin - Qrej = 1953.5 kW must equal Wnet = 1953.5 kW

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	1400	1400	0	OK
State 1	h_kJ_kg	3153.87	3153.87	0	OK
State 1	mdot_kg_s	4	4	0	OK
State 2	P_kPa	1385	1385	0	OK
State 2	h_kJ_kg	3291.5	3291.5	1.1054e-06	OK
State 3	P_kPa	1365	1365	0	OK
State 3	h_kJ_kg	5322.43	5322.43	0	OK
State 4	P_kPa	350	350	0	OK
State 4	h_kJ_kg	3312.54	3312.54	4.57035e-08	OK
State 5	P_kPa	335	335	0	OK
State 5	h_kJ_kg	3174.91	3174.91	-1.0597e-06	OK
State 6	P_kPa	325	325	0	OK
State 6	h_kJ_kg	1632.35	1632.35	0	OK

Cycle summary comparison

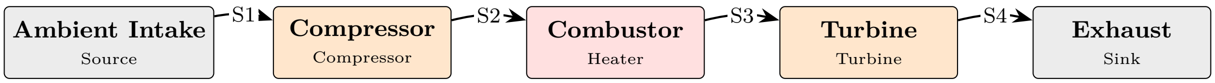
Cycle quantity	Hand	Software	Diff	Status
heat_input_kW	8123.7	8123.7	-4.4216e-06	OK
gross_work_kW	8039.56	8039.56	-1.82814e-07	OK
parasitic_work_kW	6086.11	6086.11	0	OK
net_work_kW	1953.45	1953.45	-1.82814e-07	OK
heat_rejected_kW	6170.24	6170.24	-4.23878e-06	OK
thermal_efficiency	0.240463	0.240463	1.08377e-10	OK

10 [T8] Open Brayton cycle (Air)

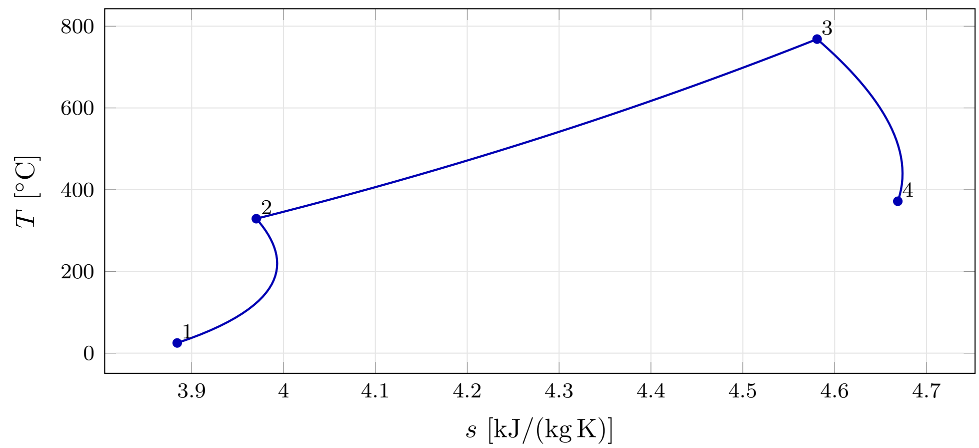
5-component open gas turbine: ambient source 100 kPa / 25 °C / 12 kg/s, compressor to 900 kPa (eta 0.84), combustor as Duty-mode heater (6 MW fuel, 97% efficiency → 5.82 MW absorbed, dP 25 kPa), turbine to 102 kPa (eta 0.89), exhaust sink.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (Air)



Hand calculation

- State 1: 100 kPa, 25 C → h1 = 424.44, s1 = 3.88428
- State 2: h2s = 685.81; h2 = h1 + (h2s - h1)/0.84 = 735.59, T2 = 329.00 C
- State 3 (Duty mode): h3 = h2 + eff*Q/m = h2 + 0.97*6000/12 = 1220.59, T3 = 768.43 C (heat absorbed = 5820 kW)
- State 4: h4s = 726.41; h4 = h3 - 0.89(h3 - h4s) = 780.77, T4 = 371.68 C
- Qin(absorbed) = 5820.0 kW; Wturb = 5277.8 kW; Wcomp = 3733.8 kW; eta = 0.26529

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P__kPa	100	100	0	OK
State 1	T__C	25	25	-1.58593e-11	OK
State 1	h__kJ__kg	424.439	424.439	0	OK
State 1	mdot__kg__s	12	12	0	OK
State 2	P__kPa	900	900	0	OK

State 2	h_kJ_kg	735.59	735.59	-9.31095e-10	OK
State 2	mdot_kg_s	12	12	0	OK
State 3	P_kPa	875	875	0	OK
State 3	h_kJ_kg	1220.59	1220.59	-9.31095e-10	OK
State 3	T_C	768.428	768.428	-8.09678e-10	OK
State 4	P_kPa	102	102	0	OK
State 4	h_kJ_kg	780.771	780.771	5.23869e-10	OK
State 4	T_C	371.676	371.676	4.93628e-10	OK

Cycle summary comparison

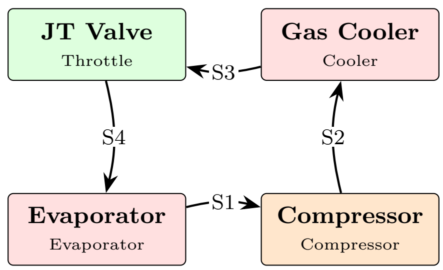
Cycle quantity	Hand	Software	Diff	Status
heat_input_kW	5820	5820	0	OK
gross_work_kW	5277.82	5277.82	-1.74596e-08	OK
parasitic_work_kW	3733.81	3733.81	-1.11731e-08	OK
thermal_efficiency	0.265294	0.265294	-1.08014e-12	OK

11 [T9] Transcritical CO2 heat pump with JT throttle

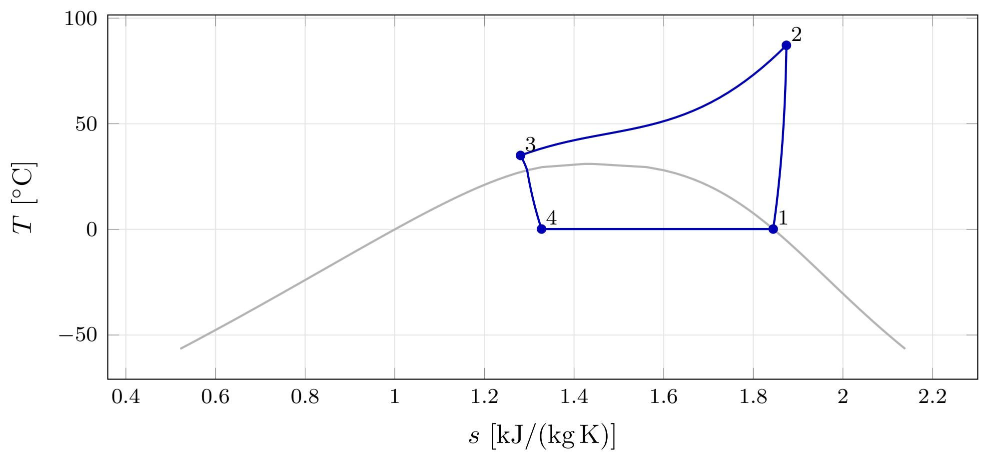
4-component transcritical CO2 cycle: evaporator to saturated vapor at 3.5 MPa, compressor to 10 MPa (supercritical, eta 0.80), gas cooler to 35 °C, Joule-Thomson throttle back to 3.5 MPa. mdot = 0.5 kg/s.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (CO2)



Hand calculation

- State 1: sat vapor 3.5 MPa (Tsat = 0.16 C): h1 = 430.799, s1 = 1.84440
- State 2: h2s = 472.964; h2 = h1 + (h2s - h1)/0.80 = 483.505, T2 = 87.13 C (supercritical)
- State 3 (gas cooler out): h(10 MPa, 35 C) = 289.518 (supercritical liquid-like)
- State 4 (JT): h4 = h3 = 289.518 → x4 = 0.3868 at Tsat = 0.16 C (JT temperature drop = 34.84 K)
- Qevap = 70.64 kW; Wcomp = 26.35 kW; COP = 2.6806

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status

State 1	P_kPa	3500	3500	0	OK
State 1	h_kJ_kg	430.799	430.799	0	OK
State 1	mdot_kg_s	0.5	0.5	0	OK
State 2	P_kPa	10000	10000	0	OK
State 2	h_kJ_kg	483.505	483.505	0	OK
State 2	T_C	87.1325	87.1325	0	OK
State 3	P_kPa	10000	10000	0	OK
State 3	h_kJ_kg	289.518	289.518	0	OK
State 3	T_C	35	35	-6.29257e-11	OK
State 4	P_kPa	3500	3500	0	OK
State 4	h_kJ_kg	289.518	289.518	0	OK
State 4	x	0.386817	0.386817	0	OK

Cycle summary comparison

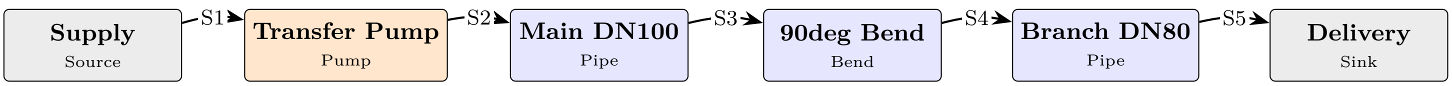
Cycle quantity	Hand	Software	Diff	Status
heat_input_kW	70.6407	70.6407	0	OK
parasitic_work_kW	26.353	26.353	0	OK
refrigeration_COP	2.68056	2.68056	0	OK

12 [F1] Pumped water transfer line (turbulent Darcy-Weisbach)

6-component open hydraulic line: 300 kPa / 20 °C / 12 kg/s source, pump to 1200 kPa (eta 0.75), 85 m of DN100 pipe (K = 2.5), a 90-degree bend with geometry-computed K, then 40 m of DN80 pipe into a sink.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



Reading the diagram — coincident states. This is physics, not a plotting error. States 3, 4 coincide at plot scale ($\Delta T = 0.00$ K, $\Delta s = 0.0000$ kJ/(kg K), $\Delta P = 1$ kPa, $\Delta h = 0.00$ kJ/kg): a junction (splitter) duplicates the thermodynamic state - only the mass flows differ.

Hand calculation

- State 1: 300 kPa, 20 C: h1 = 84.194, rho = 998.30 kg/m3
- State 2 (pump out): h2 = h1 + (h(1.2 MPa, s1) - h1)/0.75 = 85.3960 kJ/kg (pump work = 14.422 kW)
- Pipe A at inlet state: rho = 998.69, V = 1.5299 m/s, Re = 1.529e+05, f(Swamee-Jain) = 0.01918, dP = (fL/D + K) rho V^2/2 = 21.9794 kPa
- Bend: Re = 1.529e+05, f = 0.01918, Le/D = 30, K = f*Le/D = 0.57550, dP = 0.67262 kPa
- Pipe B: V = 2.3905 m/s, Re = 1.912e+05, f = 0.02417, dP = 34.4850 kPa
- Delivery pressure: P5 = 1200 - 21.979 - 0.6726 - 34.485 = 1142.863 kPa

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	300	300	0	OK
State 1	T_C	20	20	-2.95586e-12	OK
State 1	h_kJ_kg	84.1942	84.1942	0	OK
State 1	mdot_kg_s	12	12	0	OK
State 2	P_kPa	1200	1200	0	OK
State 2	h_kJ_kg	85.396	85.396	-4.76774e-11	OK
State 3	P_kPa	1178.02	1178.02	-1.87356e-10	OK
State 3	h_kJ_kg	85.396	85.396	-4.76774e-11	OK
State 4	P_kPa	1177.35	1177.35	-1.9395e-10	OK
State 4	h_kJ_kg	85.396	85.396	-4.76774e-11	OK
State 5	P_kPa	1142.86	1142.86	-1.95769e-10	OK
State 5	h_kJ_kg	85.396	85.396	-4.76774e-11	OK

Cycle summary comparison

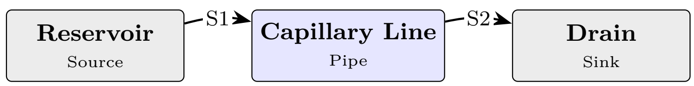
Cycle quantity	Hand	Software	Diff	Status
PipeA Re	152914	152914	-1.51286e-05	OK
PipeA f	0.0191835	0.0191835	2.07365e-13	OK
PipeA dP__kPa	21.9794	21.9794	1.87388e-10	OK
Bend K	0.575498	0.575498	6.03129e-12	OK
Bend dP__kPa	0.672619	0.672619	6.58229e-12	OK
PipeB dP__kPa	34.485	34.485	1.79057e-12	OK

13 [F2] Laminar micro-flow line (f = 64/Re)

Smallest system: source → pipe → sink. Water at 0.005 kg/s in a 20 mm line, 30 m long: Re approx 320, laminar regime, f = 64/Re.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



Hand calculation

- V = m/(rho A) = 0.01594 m/s; Re = rho V D / mu = 317.81 < 2300 → laminar
- f = 64/Re = 0.20138; dP = f (L/D) rho V^2 / 2 = 38.325 Pa

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	150	150	0	OK
State 1	T_C	20	20	-3.86535e-12	OK
State 1	h_kJ_kg	84.0531	84.0531	0	OK
State 1	mdot_kg_s	0.005	0.005	0	OK
State 2	P_kPa	149.962	149.962	0	OK
State 2	h_kJ_kg	84.0531	84.0531	0	OK

Cycle summary comparison

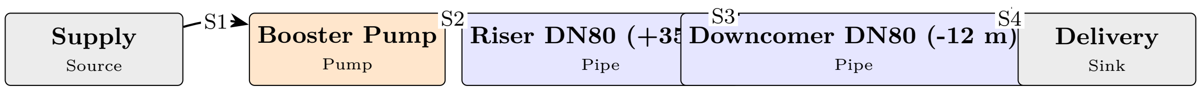
Cycle quantity	Hand	Software	Diff	Status
Re	317.807	317.807	0	OK
f = 64/Re	0.20138	0.20138	0	OK
dP_kPa	0.0383254	0.0383254	1.11855e-14	OK

14 [F3] Pumped riser and downcomer (elevation head)

5-component hydraulic loop over terrain: 250 kPa / 15 °C / 6 kg/s source, pump to 1000 kPa (eta 0.70), a 60 m DN80 riser climbing +35 m, then a 25 m DN80 downcomer descending -12 m into a sink. Verifies the rho*g*dz static head (signed) in the pressure balance and the g*dz potential-energy term in the energy balance.

Solver status: Fully constrained, residual RMS = 5.52e-15.

System diagram



Reading the diagram — coincident states. This is physics, not a plotting error. States 3, 4 coincide at plot scale (ΔT = 0.00 K, Δs = 0.0000 kJ/(kg K), ΔP = 113 kPa, Δh = 0.12 kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other.

Hand calculation

- State 1: 250 kPa, 15 C: h1 = 63.219
- State 2 (pump out): h2 = 64.2913
- Riser: V = 1.1942 m/s, Re = 8.417e+04, f = 0.02114; dP_fric = 11.301 kPa; dP_elev = rho g dz = 999.5 * 9.80665 * 35 / 1000 = 343.064 kPa
- State 3: P3 = 1000 - 11.301 - 343.064 = 645.635 kPa; h3 = h2 - g*35/1000 = 63.9481 (PE term = 0.3432 kJ/kg)
- Downcomer: dP_fric = 4.710 kPa; dP_elev = -117.603 kPa (negative: recovers static pressure); P4 = 758.528 kPa; h4 = 64.0657

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	250	250	0	OK
State 1	T_C	15	15	-2.86491e-11	OK
State 1	h_kJ_kg	63.2192	63.2192	0	OK
State 1	mdot_kg_s	6	6	0	OK
State 2	P_kPa	1000	1000	0	OK
State 2	h_kJ_kg	64.2913	64.2913	-3.17073e-10	OK
State 3	P_kPa	645.635	645.635	-3.75167e-12	OK
State 3	h_kJ_kg	63.9481	63.9481	-3.17065e-10	OK
State 4	P_kPa	758.528	758.528	-1.47793e-12	OK
State 4	h_kJ_kg	64.0657	64.0657	-3.17058e-10	OK

Cycle summary comparison

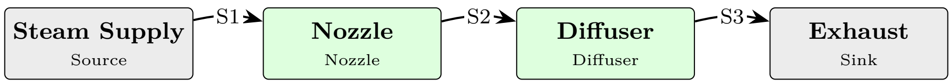
Cycle quantity	Hand	Software	Diff	Status
riser dP__kPa (fric+elev)	354.365	354.365	3.75167e-12	OK
downcomer dP__kPa (fric-elev)	-112.893	-112.893	-2.27374e-12	OK

15 [F4] Steam nozzle and diffuser train

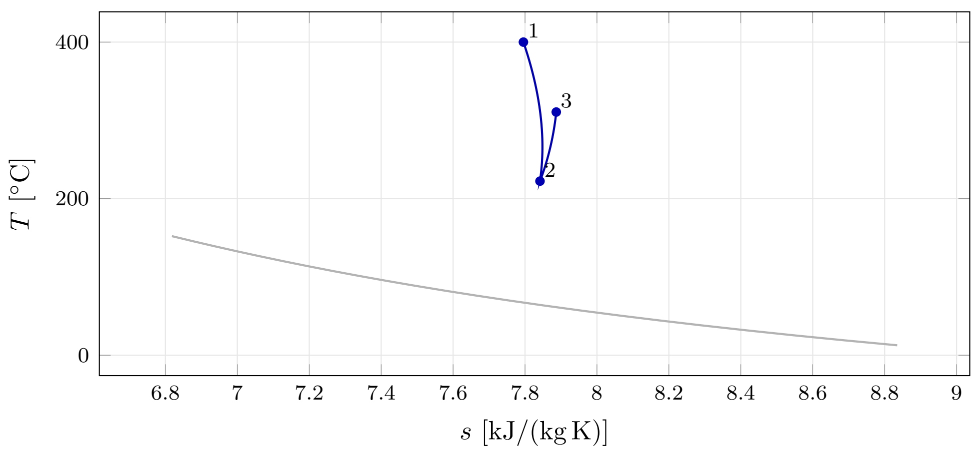
4-component compressible train: 500 kPa / 400 °C steam at 3 kg/s enters a nozzle (eta 0.94) expanding to 120 kPa, then a diffuser (eta 0.85) recovering to 220 kPa. Checks the SFEE velocity result V_out = sqrt(V_in^2 + 2000(h_in - h_out)).

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram



T–s diagram, process paths traced (Water)



Hand calculation

- State 1: 500 kPa, 400 C: h1 = 3272.350, s1 = 7.79553
- State 2: h2s = 2896.349; h2 = h1 - 0.94(h1 - h2s) = 2918.909; V2 = sqrt(40^2 + 2000(h1 - h2)) = 841.71 m/s
- State 3: h3 = h2 + (h(220 kPa, s2) - h2)/0.85 = 3093.234

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P_kPa	500	500	0	OK
State 1	T_C	400	400	0	OK
State 1	h_kJ_kg	3272.35	3272.35	0	OK
State 1	mdot_kg_s	3	3	0	OK
State 2	P_kPa	120	120	0	OK
State 2	h_kJ_kg	2918.91	2918.91	0	OK
State 3	P_kPa	220	220	0	OK
State 3	h_kJ_kg	3093.23	3093.23	0	OK

Cycle summary comparison

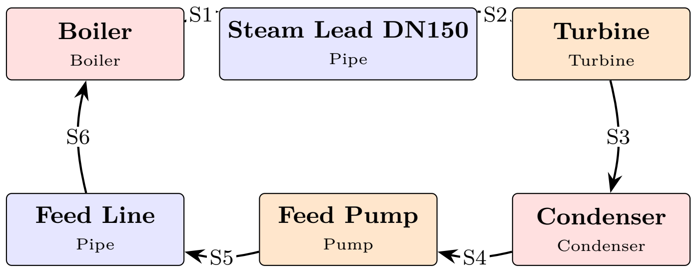
Cycle quantity	Hand	Software	Diff	Status
nozzle V__out__m__s	841.713	841.713	0	OK

16 [C1] Steam plant with real piping (combo)

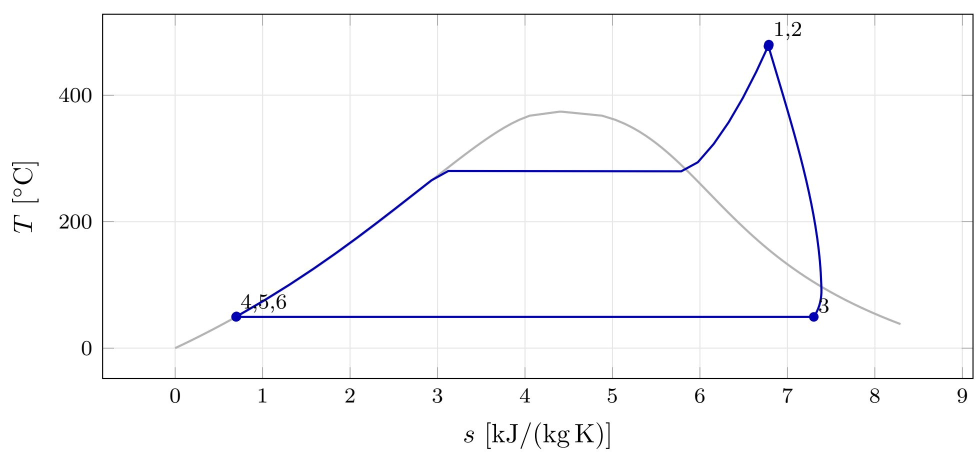
6-component combined thermo + fluids system: Rankine cycle whose steam lead is a 60 m DN150 Darcy-Weisbach pipe losing 45 kW to ambient, and whose feed line has a specified 35 kPa drop. Boiler dP 100 kPa, turbine to 12 kPa (eta 0.86), pump to 6.5 MPa (eta 0.80). mdot = 8 kg/s.

Solver status: Fully constrained, residual RMS = 7.42e-14.

System diagram



T–s diagram, process paths traced (Water)



Reading the diagram — coincident states. This is physics, not a plotting error. States 1, 2 coincide at plot scale ($\Delta T = 2.52$ K, $\Delta s = 0.0049$ kJ/(kg K), $\Delta P = 37$ kPa, $\Delta h = 5.62$ kJ/kg): pipe/fitting friction moves pressure, not temperature or entropy, so consecutive hydraulic states coincide on a T-s axis. States 4, 5, 6 coincide at plot scale ($\Delta T = 0.63$ K, $\Delta s = 0.0052$ kJ/(kg K), $\Delta P = 6488$ kPa, $\Delta h = 8.20$ kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other.

Hand calculation

- State 1 (boiler out): P1 = 6500 - 35 - 100 = 6365 kPa, 480 C → h1 = 3370.749
- Steam lead: rho = 19.395 kg/m3, V = 23.34 m/s, Re = 2.433e+06, f = 0.01765, dP = 37.305 kPa; h2 = h1 - 45/8 = 3365.124

- State 3 (turbine out): h3s = 2170.367; h3 = h2 - 0.86(h2 - h3s) = 2337.633; x3 = 0.8940
- State 4: sat liquid 12 kPa: h4 = 206.911
- State 5 (pump out): h5 = 215.1057
- State 6 (feed line out): P6 = 6500 - 35 = 6465 kPa, h6 = h5 (no heat loss)
- Qin = 25245.1 kW; Wt = 8219.9 kW; Wp = 65.56 kW; Qrej,total = m(h3 - h4) + 45 = 17090.8 kW
- First law: Qin - Qrej,total = 8154.37 kW = Wnet = 8154.37 kW

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P__kPa	6365	6365	-3.10138e-10	OK
State 1	h__kJ__kg	3370.75	3370.75	6.18911e-10	OK
State 1	mdot__kg__s	8	8	3.55271e-15	OK
State 2	P__kPa	6327.7	6327.7	-4.03816e-10	OK
State 2	h__kJ__kg	3365.12	3365.12	9.76797e-10	OK
State 3	P__kPa	12	12	0	OK
State 3	h__kJ__kg	2337.63	2337.63	-6.23004e-11	OK
State 3	x	0.894003	0.894003	-2.63123e-14	OK
State 4	P__kPa	12	12	0	OK
State 4	h__kJ__kg	206.911	206.911	0	OK
State 5	P__kPa	6500	6500	-1.02773e-10	OK
State 5	h__kJ__kg	215.106	215.106	0	OK
State 6	P__kPa	6465	6465	-2.06455e-10	OK
State 6	h__kJ__kg	215.106	215.106	0	OK

Cycle summary comparison

Cycle quantity	Hand	Software	Diff	Status
heat__input__kW	25245.1	25245.1	4.9622e-09	OK
gross__work__kW	8219.93	8219.93	8.31642e-09	OK
parasitic__work__kW	65.5608	65.5608	2.84217e-14	OK
heat__rejected__kW (incl. pipe loss)	17090.8	17090.8	-4.91127e-10	OK

17 [C2] Two-loop project: Rankine + VCR side by side

9-component, two-fluid-loop project: a small water Rankine loop (4 comps) and an independent R134a VCR loop (4 comps, 0.06 kg/s) solved in one project. Verifies multi-loop aggregation: states keep their loop's fluid, summaries combine.

Solver status: Fully constrained, residual RMS = 0.00e+00.

System diagram

Reading the diagram — coincident states. This is physics, not a plotting error. States 3, 4 coincide at plot scale ($\Delta T = 0.38$ K, $\Delta s = 0.0027$ kJ/(kg K), $\Delta P = 3980$ kPa, $\Delta h = 4.93$ kJ/kg): liquid compression: raising the pressure of a nearly incompressible liquid costs $w \approx v\,\Delta P$ with almost no temperature or entropy change, so pump inlet and outlet plot on top of each other.

Hand calculation

- Steam loop: h1 = 3331.175, h2 = 2442.935, h3 = 251.423, h4 = 256.356
- R134a loop: h1 = 394.085, h2 = 433.498, h3 = 255.496, h4 = h3 = 255.496
- Combined: Qin = 9224.5 + 8.32 kW; net work = 2649.9 - 2.36 kW

State-by-state comparison

State	Quantity	Hand	Software	Diff	Status
State 1	P__kPa	4000	4000	0	OK
State 1	h__kJ__kg	3331.17	3331.17	0	OK
State 1	mdot__kg__s	3	3	0	OK
State 2	P__kPa	20	20	0	OK
State 2	h__kJ__kg	2442.94	2442.94	0	OK
State 3	P__kPa	20	20	0	OK
State 3	h__kJ__kg	251.423	251.423	0	OK
State 4	P__kPa	4000	4000	0	OK
State 4	h__kJ__kg	256.356	256.356	0	OK
State 5	P__kPa	220	220	0	OK
State 5	h__kJ__kg	394.085	394.085	0	OK
State 5	mdot__kg__s	0.06	0.06	0	OK
State 6	P__kPa	1000	1000	0	OK
State 6	h__kJ__kg	433.498	433.498	0	OK
State 7	P__kPa	1000	1000	0	OK
State 7	h__kJ__kg	255.496	255.496	0	OK

State 8	P__kPa	220	220	0	OK
State 8	h__kJ__kg	255.496	255.496	0	OK

Cycle summary comparison

Cycle quantity	Hand	Software	Diff	Status
heat__input__kW	9232.77	9232.77	0	OK
net__work__kW	2647.55	2647.55	0	OK
steam loop net__work__kW	2649.92	2649.92	0	OK
R134a loop COP	3.51635	3.51635	0	OK