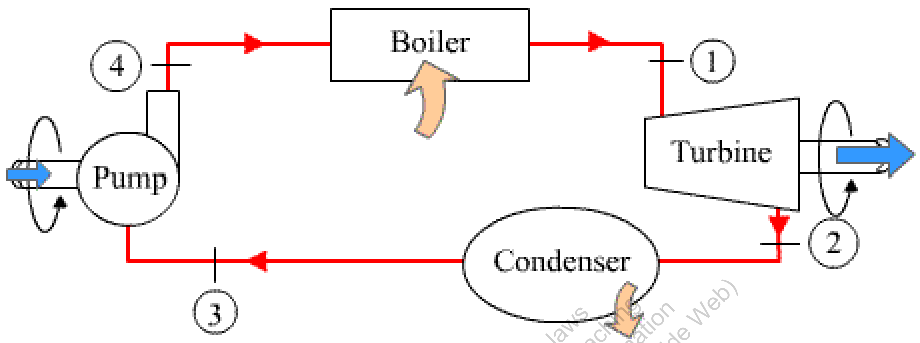
9-3-1 [OXZ] Consider a steam power plant operating on the simple ideal Rankine cycle. Steam enters the turbine at 4 MPa, 400°C and is condensed in the condenser at a pressure of 100 kPa. The mass flow rate is 10 kg/s. If the boiler receives heat from a source at 1200°C and the condenser rejects heat to a reservoir at 25°C, determine (a) the thermal efficiency of the cycle, (b) the exergetic efficiency of the cycle and (c) draw an exergy flow diagram for the cycle. Assume the atmospheric conditions to be 100 kPa and 25°C.

SOLUTION:



Heat Source at 1200 °C (1473 K)

Dead State: p0 = 100 kPa and T0 = 25 °C (298 K)

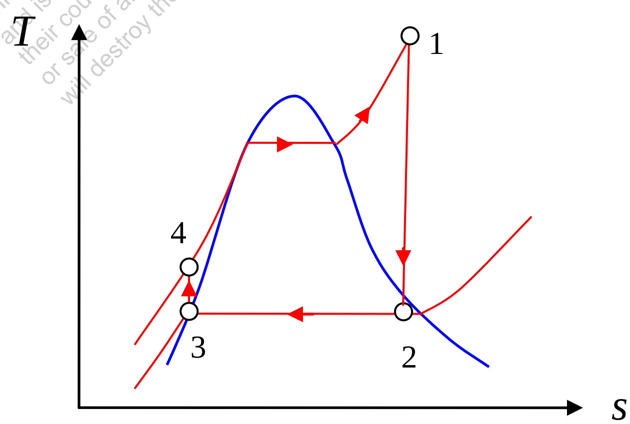


Table 1 Properties at various state points in the steam power plant at rated conditions

	p kPa	T K	$\dot{\Psi} = \dot{m}\psi$ MW	s kJ/$\left(\text{kg}\cdot\text{K}\right)$	h kJ/kg
State 0	**100**	**298**	0	0.36732	104.9787
State 1	**4000**	**673**	11.9988	6.7686	3213.48
State 2	**100**	372	4.4174	**6.7686**	2455.34
State 3	**100**	372	0.33636	1.3025	417.44
State 4	**100**	372	0.37703	**1.3025**	478.99313

Note: Green quantities are given and black quantities are calculated.

Table 2 Device-specific analysis

Plant Component	Device	$\lvert\Delta\dot{\Psi}\rvert$ MW	$\dot{W}_u$ MW	Exergy Supplied from Reservoir MW	$\dot{I}$ MW	Exergetic Efficiency %
Turbine	A	7.5814	+ 7.5814	0	0	100
Condenser	B	4.08104	0	0	4.08104	0
Pump	C	0.04067	-0.04067	0	0	100
Boiler	D	11.6217	0	22.27138	10.64968	52.182
Total Plant			7.54073	22.27138	14.73072	33.86

(a) In order to determine the thermal efficiency, η_{th}, the Cycle Panel from TEST was used.

$$\dot{W}_{net} = 7540.73 \text{ kW}$$
$$\dot{Q}_{in} = 27919.78 \text{ kW}$$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{7540.73 \text{ kW}}{27919.78 \text{ kW}} = 0.27 = 27\%$$

(b) Rate of exergy supplied by the reservoir at 1473 K,

$$\dot{Q}_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 27.919 \text{ MW} \times (1\text{-}\frac{298\text{K}}{1473\text{K}}) = 22.271 \text{ MW}$$

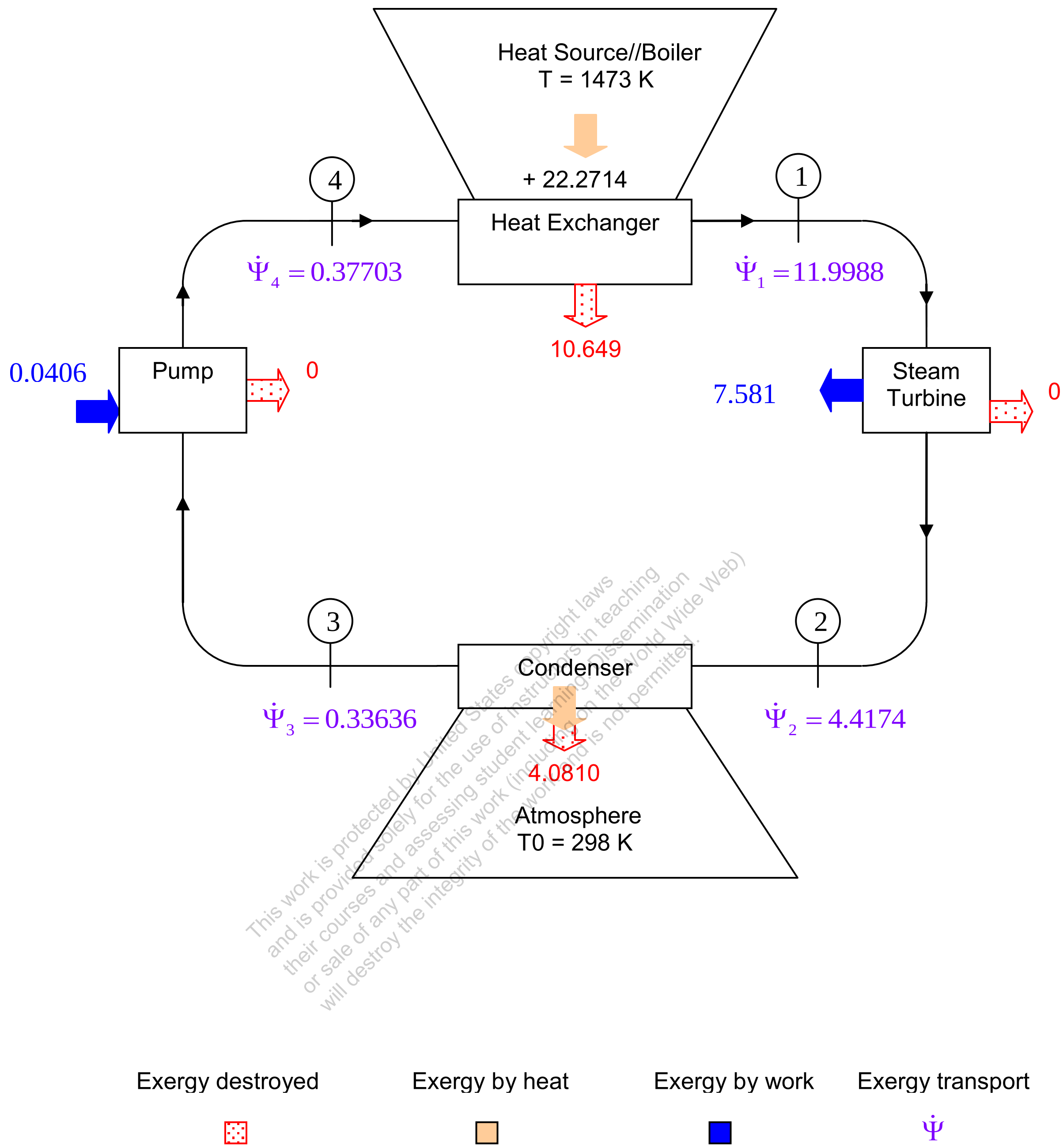
To calculate the exergetic efficiency, η_{II} ,

$$\dot{W}_{net} = 7540.73 \text{ kW}$$

$$\dot{W}_{\text{max}} = \dot{W}_{\text{rev}} = \dot{W}_{\text{net}} + \dot{I}$$

$$\dot{W}_{\text{max}} = 7540.73 + 14730.72 = 22271.4 \text{ kW}$$

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\text{max}}} = \frac{7540.73 \text{ kW}}{22271.4 \text{ kW}} = 0.3386 = 33.86\%$$

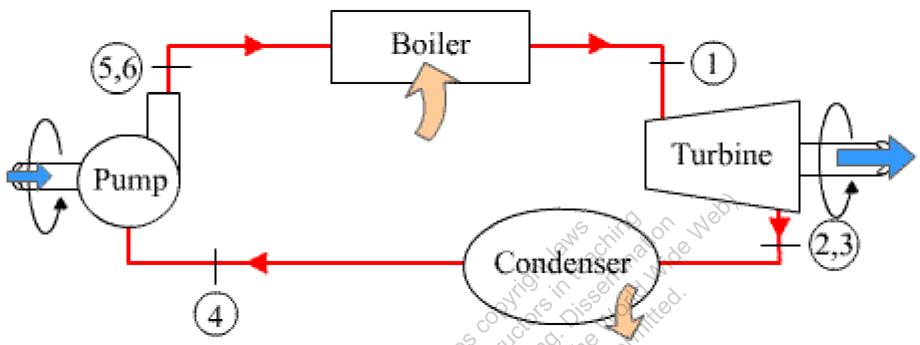


Exergy diagram for the total plant (*on MW basis*)

TEST Solution Use the PC vapor-power cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

9-3-2 [OXK] Steam is the working fluid in an ideal Rankine cycle. Saturated vapor enters the turbine at 10 MPa and saturated liquid exits the condenser at a pressure of 0.01 MPa. The net power output ($\dot{W}_{net}$) of the cycle is 150 MW. The turbine and the pump both have an isentropic efficiency of 85%. If the boiler receives heat from a source at 1200°C and the condenser rejects heat to a reservoir at 25°C, (a) identify the device of maximum exergy destruction (boiler: 0; turbine: 1; condenser: 3; pump: 4), (b) determine the exergetic efficiency of the cycle and (c) draw an exergy flow diagram for the cycle. Assume the atmospheric conditions to be 100 kPa and 25°C.

SOLUTION:



Heat Source at 1200 °C (1473 K)

Dead State: p0 = 100 kPa and T0 = 25 °C (298 K)

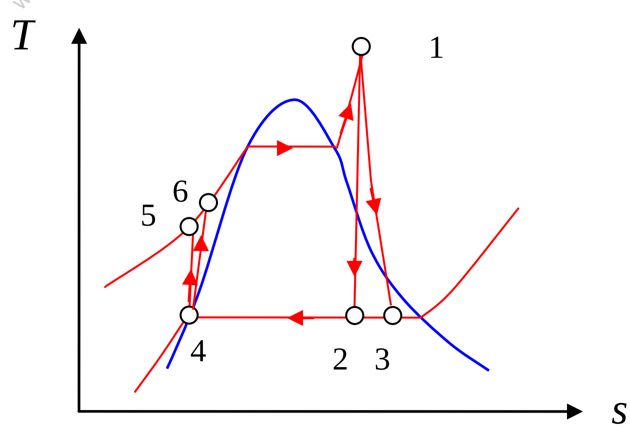


Table 1 Properties at various state points in the steam power plant at rated conditions

	p kPa	T K	$\dot{\Psi} = \dot{m}\psi$ MW	s kJ/(kg·K)	h kJ/kg
State 0	**100**	**298**	0	0.36732	104.9787
State 1	**10000**	**584**	199.46	5.6141	2724.67
State 2	**10**	319	20.095	**5.6141**	1775.63
State 3	**10**	319	21.854	6.06035	**1917.98**
State 4	**10**	319	0.52502	0.6493	191.8298
State 5	**10000**	319	2.43201	**0.6493**	201.9197
State 6	**10000**	319	2.45637	0.65484	**203.7**

Note: Green quantities are given and black quantities are calculated.

Table 2 Device-specific analysis

Plant Component	Device	$\lvert\Delta\dot{\Psi}\rvert$ MW	$\dot{W}_u$ MW	Exergy Supplied from Reservoir MW	$\dot{I}$ MW	Exergetic Efficiency %	Plant Component
Turbine	A	177.60	+ 152.46	0	25.143	6.6153	86
Condenser	B	21.328	0	0	21.3289	5.6118	0
Pump	C	1.93135	-2.2435	0	0.31216	0.0821	86
Boiler	D	197	0	380.07	183.07	48.1674	52.182
Total Plant			150.21	380.07	229.854	60.4766	39.52

In order to determine the thermal efficiency, η_{th}, the Cycle Panel from TEST was used.

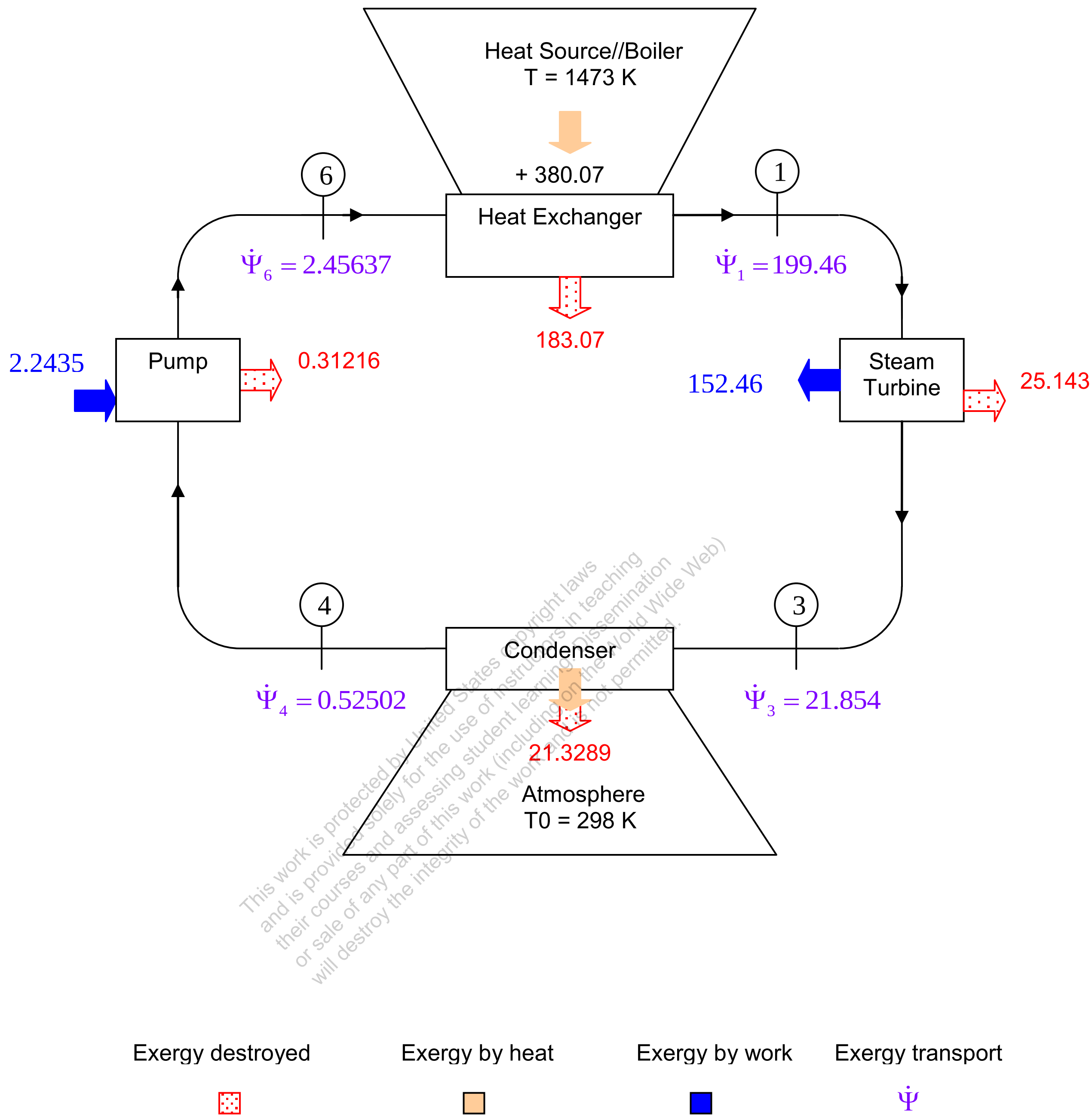
$\dot{W}_{net} = 150210 \text{ kW}$
$\dot{Q}_{in} = 476463 \text{ kW}$
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{150210 \text{ kW}}{476463 \text{ kW}} = 0.3152 = 31.52\%$$

(a) Maximum exergy is destroyed in boiler, 183.07 MW and exergetic efficiency of boiler is 52.2 %.

(b) Rate of exergy supplied by the reservoir at 1473 K,
$$\dot{Q}_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 476.46 \text{ MW} \times (1 - \frac{298\text{K}}{1473\text{K}}) = 380.07 \text{ MW}$$

To calculate the exergetic efficiency, η_{II} ,

$\dot{W}_{net} = 150000 \text{ kW}$
$\dot{W}_{\max} = \dot{W}_{\text{rev}} = \dot{W}_{\text{net}} + \dot{I} = 150210 + 229854 = 380064 \text{ kW}$
$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{150210 \text{ kW}}{380064 \text{ kW}} = 0.3952 = 39.52\%$$

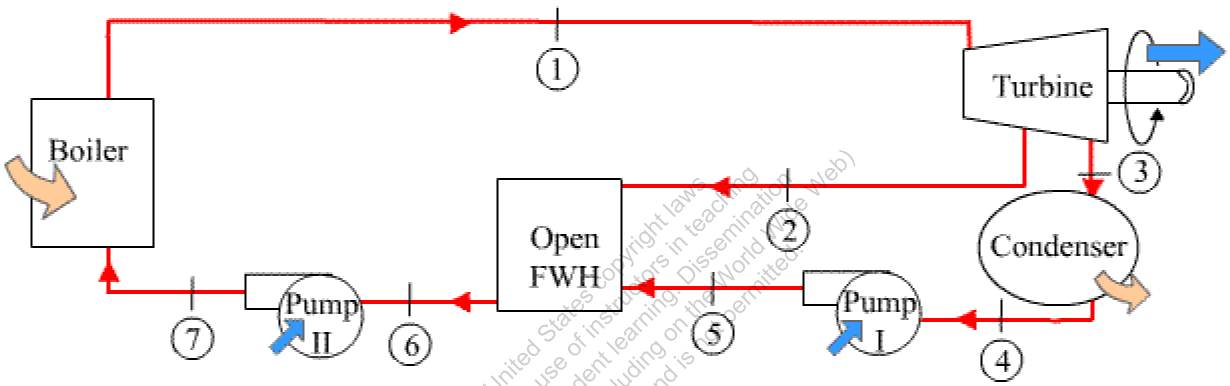


Exergy diagram for the total plant (*on MW basis*)

TEST Solution Use the PC vapor-power cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

9-3-3 [OXP] In a steam power plant operating on the ideal regenerative Rankine cycle with one open feedwater heater, steam enters the turbine at 9 MPa, 480°C and is condensed in the condenser at a pressure of 7 kPa. Bleeding from the turbine to the FWH occurs at 0.7 MPa. The net power output ($\dot{W}_{net}$) of the cycle is 100 MW. The boiler receives heat from a source at 1200°C and the condenser rejects heat to atmosphere at 100 kPa, 25°C. (a) Perform an exergy inventory and draw an exergy flow diagram for the cycle. Determine (b) the thermal efficiency (η_{th}) and (c) exergetic efficiency of the cycle.

SOLUTION:



Heat Source at 1200 °C (1473 K)

Dead State: p0 = 100 kPa and T0 = 25 °C (298 K)

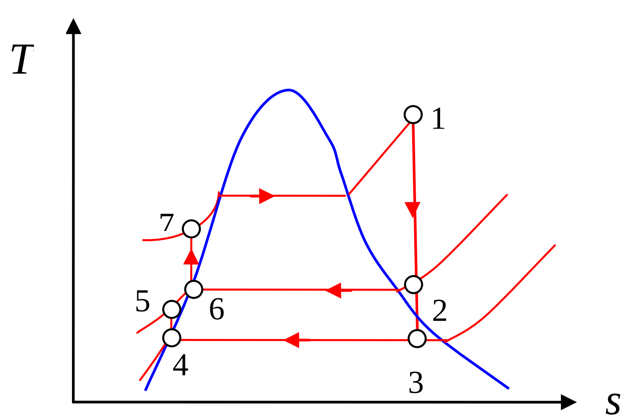


Table 1 Properties at various state points in the steam power plant at rated conditions

	p kPa	T K	$\dot{\Psi} = \dot{m}\psi$ MW	s $\mathrm{kJ/(kg \cdot K)}$	h kJ/kg
State 0	**0.1**	**298**	0	0.36732	105
State 1	**9**	**753**	120.60	6.58819	3334.24
State 2	**0.7**	438	13.799	**6.58819**	2711
State 3	**0.007**	312	5.9475	**6.58819**	2045.46
State 4	**0.007**	312	0.08445	0.55893	163.33
State 5	**0.7**	312	0.13197	**0.55893**	164
State 6	**0.7**	438	9.457	1.9922	697.21
State 7	**0.1**	438	10.2639	**1.9922**	706.41

Note: Green quantities are given and black quantities are calculated.

Table 2 Device-specific analysis

Plant Component	Device	$\lvert\Delta\dot{\Psi}\rvert$ MW	$\dot{W}_u$ MW	Exergy Supplied from Reservoir MW	$\dot{I}$ MW	Exergetic Efficiency %	Plant Component
Turbine	A	100.85	+100.85	0	0	0	100
Condenser	B	5.863	0	0	5.863	3.1877	0
Pump 1	C	0.0475	-0.0475	0	0	0	100
FWH	D	4.474	0	0	4.474	2.4325	67.88
Pump 2	E	0.807	0.807	0	0	0	100
Boiler	F	110.336	0	+183.92	73.588	40.01	60
Total Plant			100	183.92	83.92	45.63	54.37

(a) Rate of exergy supplied by the reservoir at 1473K,

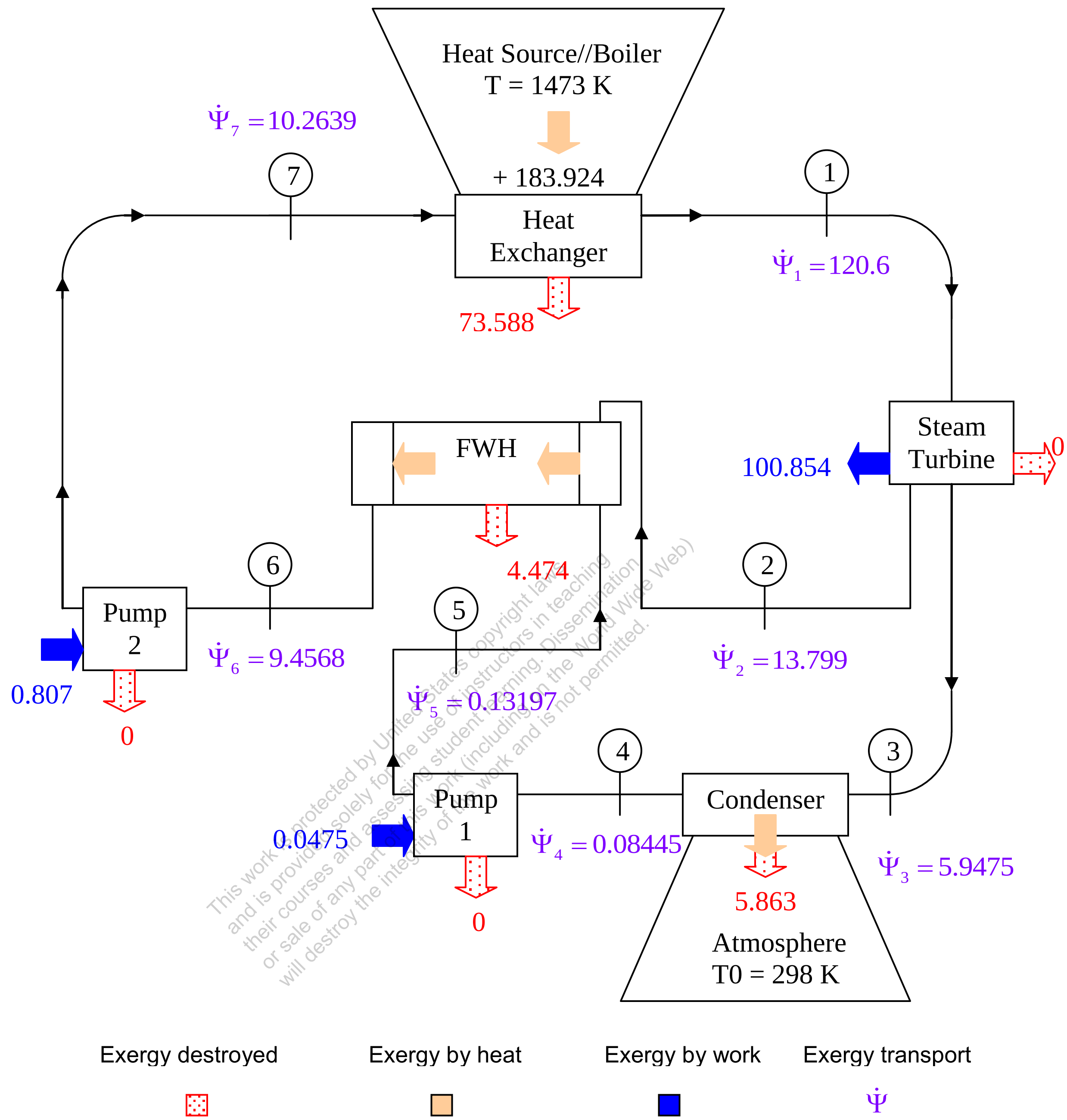
$$\dot{Q}_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 230.57\ \text{MW} \times (1\text{-}\frac{298\text{K}}{1473\text{K}}) = 183.92\ \text{MW}$$

(b) In order to determine the thermal efficiency, η_{th}, the Cycle Panel from TEST was used.

$$\dot{W}_{net} = 100000 \text{ kW}$$
$$\dot{Q}_{in} = 230571 \text{ kW}$$
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{100000 \text{ kW}}{230571 \text{ kW}} = 0.4337 = 43.37\%$$

(c) To calculate the exergetic efficiency, η_{II},

$$\dot{W}_{net} = 100000 \text{ kW}$$
$$\dot{W}_{\text{max}} = \dot{W}_{\text{rev}} = \dot{W}_{\text{net}} + \dot{I}$$
$$\dot{W}_{\text{max}} = 100000 + 83924 = 183924 \text{ kW}$$
$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\text{max}}} = \frac{100000 \text{ kW}}{183924 \text{ kW}} = 0.5437 = 54.37\%$$

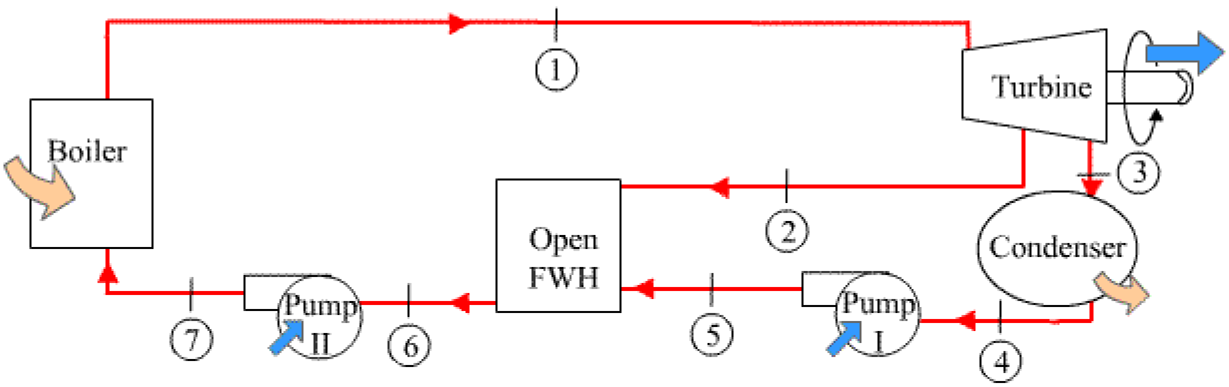


Exergy diagram for the total plant (*on MW basis*)

TEST Solution Use the PC vapor-power cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

9-3-4 [OXU] Repeat problem 9-3-3 [OXP], assuming no steam is bled from the turbine for regeneration.

SOLUTION:



Heat Source at 1200 °C (1473 K)

Dead State: p0 = 100 kPa and T0 = 25 °C (298 K)

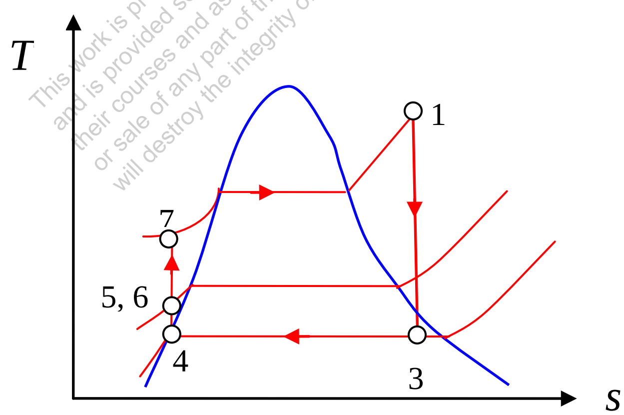


Table 1 Properties at various state points in the steam power plant at rated conditions

	p kPa	T K	$\dot{\Psi} = \dot{m}\psi$ MW	s $\text{kJ}/(\text{kg}\cdot\text{K})$	h kJ/kg
State 0	**0.1**	**298**	0	0.36732	105
State 1	**9**	**753**	107.404	6.58819	3334.24
State 2	**0.7**	438	0	**6.58819**	2711
State 3	**0.007**	312	6.69910	**6.58819**	2045.46
State 4	**0.007**	312	0.09513	0.55893	163.33
State 5	**0.7**	312	0.14865	**0.55893**	164.011
State 6	**0.7**	**312**	0.14963	0.55893	164.011
State 7	**0.1**	312	0.80187	**0.55893**	172.358

Note: Green quantities are given and black quantities are calculated.

Table 2 Device-specific analysis

Plant Component	Device	$\lvert\Delta\dot{\Psi}\rvert$ MW	$\dot{W}_u$ MW	Exergy Supplied from Reservoir MW	$\dot{I}$ MW	Exergetic Efficiency %	Plant Component
Turbine	A	100.70	+100.70	0	0	0	100
Condenser	B	6.6039	0	0	6.60397	3.3509	0
Pump 1	C	0.05352	-0.05352	0	0	0	100
FWH	D	N/A	N/A	N/A	N/A	N/A	N/A
Pump 2	E	0.6522	-0.6522	0	0	0	100
Boiler	F	106.60	0	+197.08	90.485	45.9128	54.08
Total Plant			100	197.08	97.08	49.2637	50.74

(a) Rate of exergy supplied by the reservoir at 1473K,

$$\dot{Q}_{\text{in}} \times \left(1 - \frac{T_o}{T_R}\right) = 247.069\ \text{MW} \times \left(1 - \frac{298\text{K}}{1473\text{K}}\right) = 197.08\ \text{MW}$$

(b) In order to determine the thermal efficiency, η_{th}, the Cycle Panel from TEST was used.

$\dot{W}_{net} = 100000 \text{ kW}$

$\dot{Q}_{in} = 247069 \text{ kW}$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{100000 \text{ kW}}{247069 \text{ kW}} = 0.4047 = 40.47\%$$

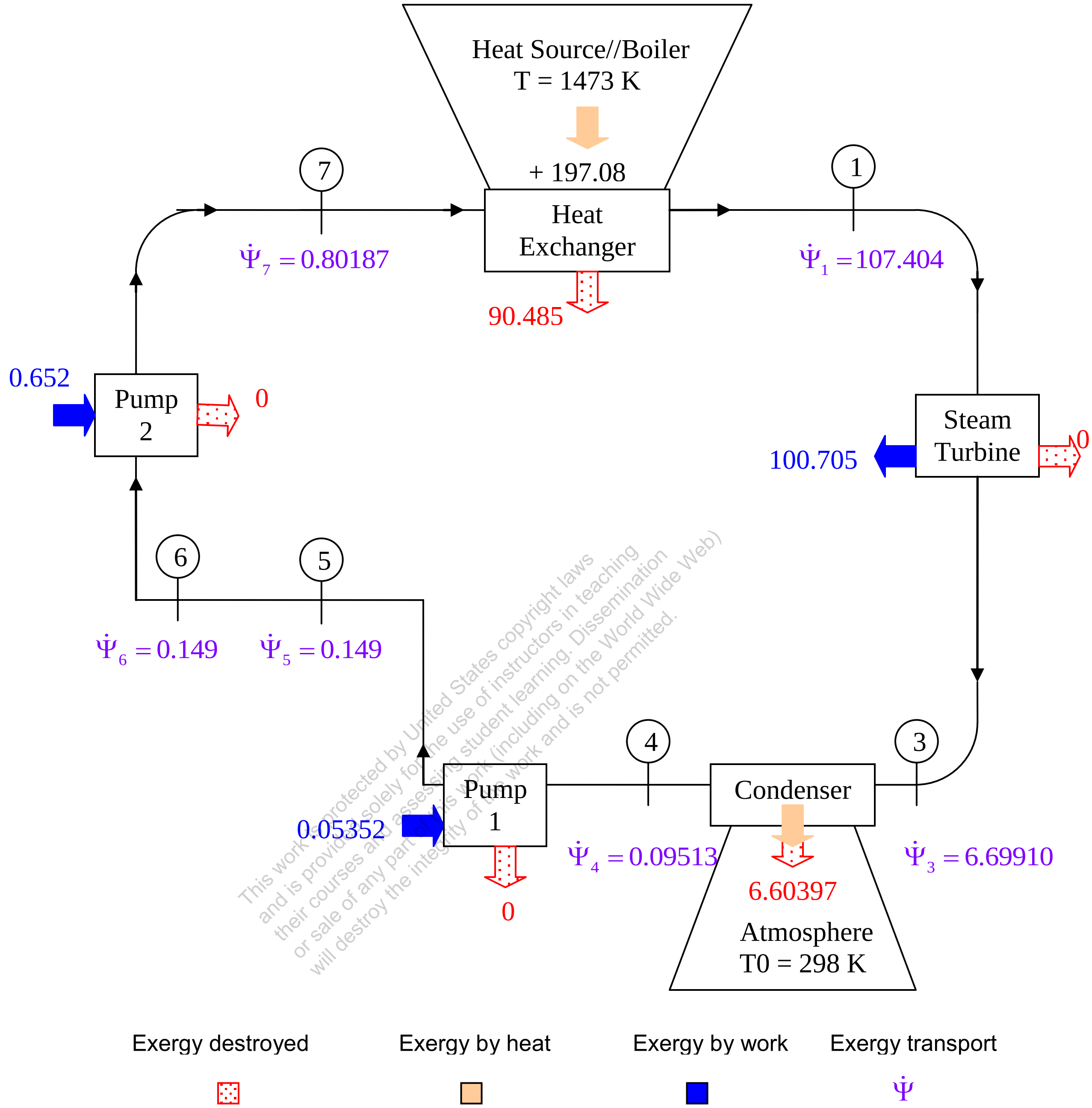
(c) To calculate the exergetic efficiency, η_{II} ,

$\dot{W}_{net} = 100000 \text{ kW}$

$\dot{W}_{\max} = \dot{W}_{\text{rev}} = \dot{W}_{\text{net}} + \dot{I}$

$\dot{W}_{\max} = 100000 + 97080 = 197080 \text{ kW}$

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{100000 \text{ kW}}{197080 \text{ kW}} = 0.5074 = 50.74\%$$

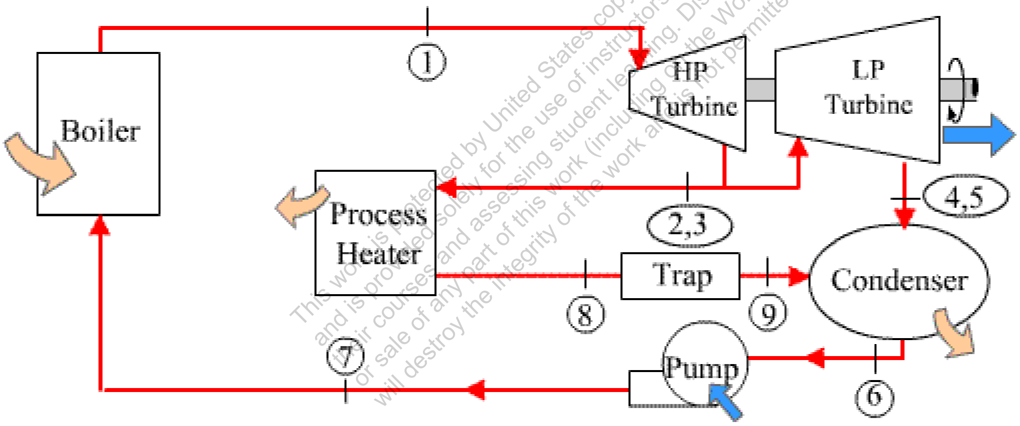


Exergy diagram for the total plant (*on MW basis*)

TEST Solution Use the PC vapor-power cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

9-3-5 [OXX] Water is the working fluid in a cogeneration cycle that generates electricity and provides heat for campus buildings. Steam at 2.5 MPa, 320°C and a mass flow rate ($\dot{m}$) of 1 kg/s, expands through a two-stage turbine. Steam at 0.2 MPa with a mass flow rate ($\dot{m}$) of 0.3 kg/s is extracted between the two stages and provided for heating. The remaining steam expands through the second stage to the condenser at a pressure of 6 kPa. The condensate returns from the campus buildings at 0.1 MPa, 60°C and passes through a trap into the condenser. Each turbine stage has an isentropic efficiency of 80%. Heat addition to the boiler takes place from a source at 1200°C, the building is maintained at 50°C, and the atmospheric conditions are 100 kPa, 20°C. (a) Perform an exergy analysis and draw an exergy flow diagram for the system. (b) Define and evaluate the exergetic efficiency of the system.

SOLUTION:



Heat Source at 1200 °C (1473 K)

Dead State: p0 = 100 kPa and T0 = 20 °C (293 K)

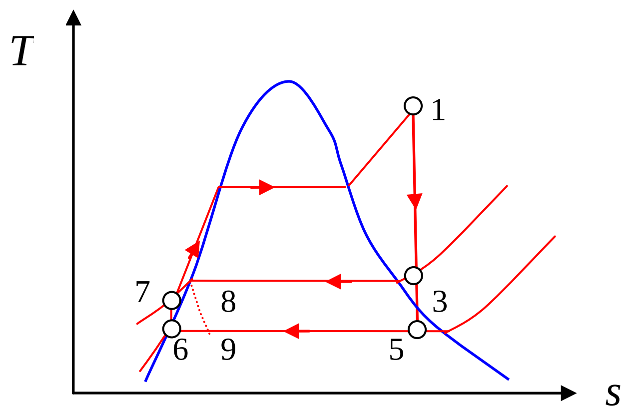


Table 1 Properties at various state points in the steam power plant at rated conditions

	p kPa	T K	$\dot{\Psi} = \dot{m}\psi$ MW	s kJ/(kg·K)	h kJ/kg
State 0	**0.1**	**293**	0	0.2966	84.0578
State 1	**2.5**	**593**	1.088	6.7223	3055.76
State 2	**0.2**	393	0.1739	**6.7223**	2547.30
State 3	**0.2**	393	0.1816	6.9807	**2648.99**
State 4	**0.006**	309	0.1062	**6.9807**	2149.75
State 5	**0.006**	309	0.0780	7.3035	**2249.60**
State 6	**0.006**	309	0.0017	0.52087	151.51
State 7	**2.5**	309	0.0042	**0.52087**	154.01
State 8	**0.1**	**333**	0.0031	0.8312	251.21
State 9	**0.2**	333	0.0031	0.83089	251.21

Note: Green quantities are given and black quantities are calculated.

Table 2 Device-specific analysis

Plant Component	Device	$\lvert\Delta\dot{\Psi}\rvert$ MW	$\dot{W}_u$ MW	Exergy Supplied from Reservoir	$\dot{I}$ MW	Exergetic Efficiency %	Plant Component

				MW			
Turbine	A	0.8284	+0.6863	0	0.1421	6.113	82.84
Condenser	B	0.07947	0	0	0.07947	3.4187	0
Pump	C	0.0025	-0.0025	0	0	0	100
Process Heater	D	0.1785	0	0	0.1785	7.679	0
Trap	E	0	0	0	0	0	0
Boiler	F	1.0838	0	+2.3245	1.24069	53.374	46.62
Total Plant			0.68383	2.3245	1.64076	70.58	29.42

(a) Rate of exergy supplied by the reservoir at 1473K,

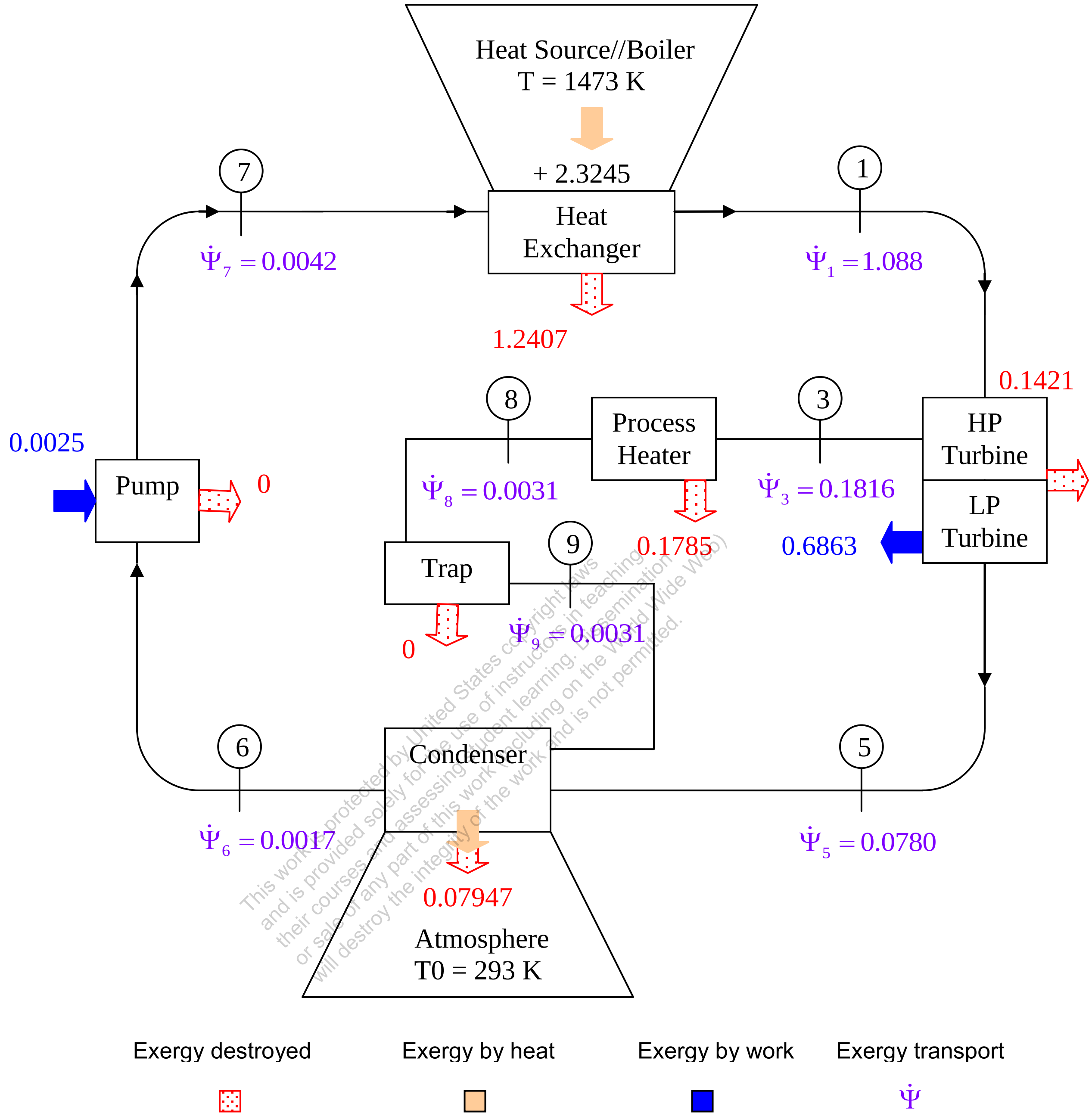
$$\dot{Q}_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 2.9017\ \text{MW} \times (1\text{-}\frac{293\text{K}}{1473\text{K}}) = 2.3245\ \text{MW}$$

(b) In order to determine the thermal efficiency, η_{th}, the Cycle Panel from TEST was used.

$$\dot{W}_{net} = 683.834\ \text{kW}$$
$$\dot{Q}_{in} = 2901.744\ \text{kW}$$
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{683.834\ \text{kW}}{2901.744\ \text{kW}} = 0.2356 = 23.56\%$$

(c) To calculate the exergetic efficiency, η_{II},

$$\dot{W}_{net} = 683.834\ \text{kW}$$
$$\dot{W}_{\max} = \dot{W}_{\text{rev}} = \dot{W}_{\text{net}} + \dot{I}$$
$$\dot{W}_{\max} = 683.834 + 1640.76 = 2324.5\ \text{kW}$$
$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{683.83\ \text{kW}}{2324.5\ \text{kW}} = 0.29418 = 29.42\%$$



Exergy diagram for the total plant (*on MW basis*)

TEST Solution Use the PC vapor-power cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.