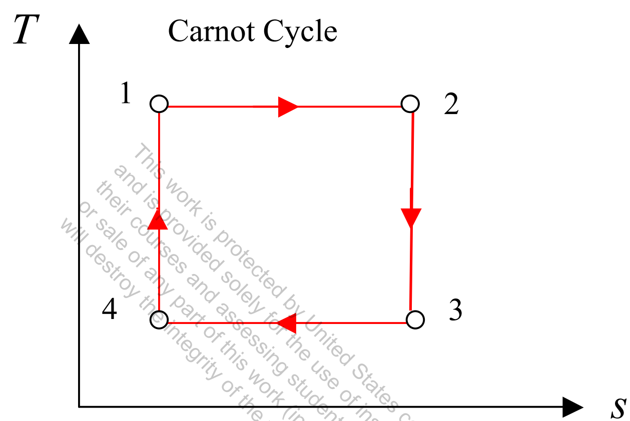
7-6-1 [OGD] A Carnot cycle running on a closed system has 1 kg of air and executes 20 cycles every second. The temperature limits are 300 K and 1000 K, and the pressure limits are 20 kPa and 1900 kPa. Atmospheric conditions are 100 kPa and 300 K. Using the PG model for air, perform a complete exergy inventory and draw an exergy flow diagram for the cycle on a rate (kW) basis. (a) What is the exergetic efficiency of the Carnot engine?

Analysis:

Dead State: P0 = 100 kPa and T0 = 27 °C (300 K)



Given:
Specific, Carnot Cycle, PG Model
Carnot engine

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in Carnot cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**300**	0	6.8929	1.856
State 1	**1900**	**1000**	321.6142	7.2560	704.30
State 2	1347	**1000**	298.199	**7.3547**	704.30
State 3	**20**	**300**	205.817	7.3547	1.8564
State 4	29	**300**	110.135	**7.2560**	1.856

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression 3-4	A	195.682	+95.6824	-125.29	-29.61656	0	0	0
Compression 4-1	B	211.478	-211.478	-290.07	-501.5552	0	0	0
Expansion Heat Addition 1-2	C	23.415	+92.5208	+6.201	+98.7218	69.10531	0	0
Expansion 2-3	D	92.381	+92.381	+409.17	+501.5552	0	0	0
Total Cycle			69.10531		69.10531	69.10531	0	0

Rate Calculations:

Exergy change during different processes:

1) ***heat addition and expansion process: 1-2***

$$\Delta\dot{\Phi} = n_{cyl}\frac{n_{cycles}}{sec}(\Phi_2 - \Phi_1) = 1\times\ 20\times(298.199-321.614) = -468.3\ \text{kW}$$

2) ***expansion process: 2-3***

$$\Delta\dot{\Phi} = n_{cyl}\frac{n_{cycles}}{sec}(\Phi_3 - \Phi_2) = 1\times\ 20\times(205.817-298.199) = -1847.62\ \text{kW}$$

3) ***heat rejection and compression process: process 3-4***

$$\Delta\dot{\Phi} = n_{cyl}\frac{n_{cycles}}{sec}(\Phi_4 - \Phi_3) = 1\times\ 20\times(110.135-205.817) = 3913.64\ \text{kW}$$

4) ***compression process: process 4-1***

$$\Delta\dot{\Phi} = n_{cyl}\frac{n_{cycles}}{sec}(\Phi_1 - \Phi_4) = 1\times\ 20\times(321.614-110.135) = 4229.56\ \text{kW}$$

Boundary work during heat rejection and compression process: process 3-4

$$W_U = (W_B - W_{atm})$$
$$W_B = -29.616562\ \text{kJ}$$
$$W_{atm} = p_0(V_4 - V_3) = 100(3.05181-4.3048) = -125.299\ \text{kJ}$$
$$W_U = -29.616562 + 125.299 = +95.682438\ \text{kJ}$$

For an engine:

$$W_U = 1913.648kW$$

Boundary work during compression process: process 4-1

$$\Delta\Phi = W_U = (W_B - W_{atm})$$
$$W_B = -501.55524\ \text{kJ}$$
$$W_{atm} = p_0(V_1 - V_4) = 100(0.15105-3.05181) = -290.076\ \text{kJ}$$
$$W_U = -501.55524 + 290.076 = -211.479\ \text{kJ}$$

For an engine:

$$W_U = 4229.58kW$$

Boundary work during heat addition and expansion process: 1-2

$$W_U = (W_B - W_{atm})$$
$$W_B = 98.72188 \text{ kJ}$$
$$W_{atm} = p_0(V_2 - V_1) = 100(0.21306 - 0.15105) = 6.201 \text{ kJ}$$
$$W_U = 98.72188 - 6.201 = 92.52088 \text{ kJ}$$

For an engine:

$$W_U = 1850.4176 kW$$

Boundary work during expansion process: 2-3

$$\Delta\Phi = W_U = (W_B - W_{atm})$$
$$W_B = 501.55524 \text{ kJ}$$
$$W_{atm} = p_0(V_3 - V_2) = 100(4.3048 - 0.21306) = 409.174 \text{ kJ}$$
$$\Delta\Phi = 501.55524 - 409.174 = +92.38124 \text{ kJ}$$

For an engine:

$$W_U = 1847.6248 kW$$

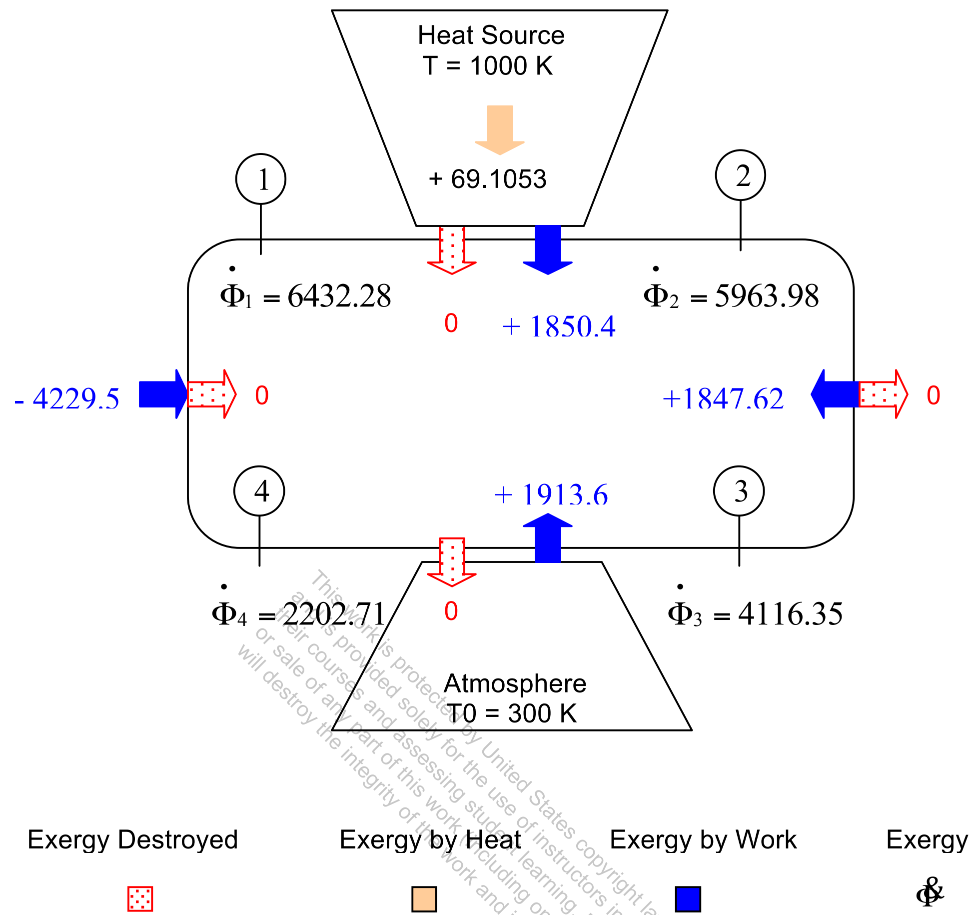
(b) Exergy supplied by the reservoir at 1000 K,

$$Q_{in} \times (1 - \frac{T_o}{T_1}) = 98.72187 \times (1 - \frac{300\text{K}}{1000\text{K}}) = 69.10531 \text{ kJ}$$

Exergy supplied by the reservoir for an engine is 1382.1062 kW

To calculate the exergetic efficiency, η_{II},

$$W_{net} = 69.10531 \text{ kJ}$$
Wmax = Wnet + Total Exergy Destroyed
Wmax = 69.10531 kJ
$$\eta_{II} = \frac{W_{net}}{\dot{W}_{max}} = \frac{69.10531 \text{ kJ}}{69.10531 \text{ kJ}} = 1 = 100\%$$



Part a: Exergy Diagram for Carnot Cycle (*on kW basis*)

TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-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.

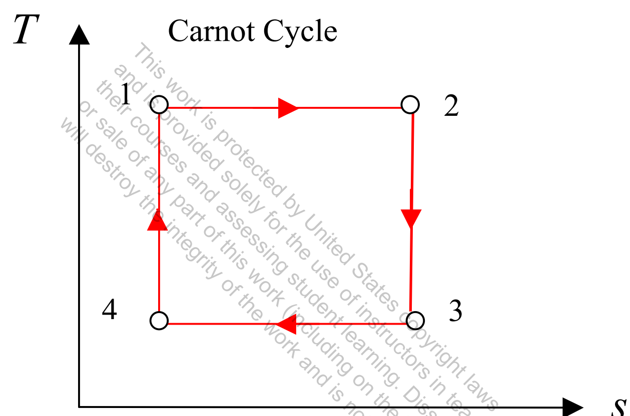
In test solution mass is taken as 1.5 kg instead of 0.5 kg.

7-6-2 [OGM] Consider a Carnot cycle executed in a closed system with 0.5 kg of air. The temperature limits are 50°C and 750°C, and the pressure limits are 15 kPa and 1700 kPa. Heat addition takes place from a reservoir at 775°C and heat rejection takes place to the atmosphere at 100 kPa, 25°C. (a) What is the exergetic efficiency of the Carnot engine? (b) Perform a complete exergy inventory and draw an exergy flow diagram for the cycle on unit mass basis (kJ/kg). Use the PG model for air.

Analysis:

Heat Source at 1048 K (775 °C)

Dead State: P0 = 100 kPa and T0 = 25 °C (298 K)



Given:
Specific, Carnot Cycle, PG Model
Carnot engine

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in Carnot cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**298**	0	6.8866	0
State 1	**1700**	**1023**	162.3412	7.31095	727.5
State 2	844	**1023**	141.1396	**7.31095**	727.5
State 3	**15**	**323**	182.0971	7.51194	25
State 4	30.21	**323**	56.3846	**7.51194**	25.08

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression 3-4	A	125.712	+123.199	-155.67	-32.47501	0	2.5225	3.428
Compression 4-1	B	105.956	-105.956	-144.82	-250.7776	0	0	0
Expansion Heat Addition 1-2	C	21.2016	+94.0606	+8.761	+102.8216	73.584	0.7256	0.98
Expansion 2-3	D	40.9575	-40.9575	+291.73	+250.7776	0	0	0
Total Cycle			70.346		70.34659	73.584	3.23741	4.399

Rate Calculations:

Boundary work during heat rejection and compression process: process 3-4

$$W_U = \left(W_B - W_{atm}\right)$$
$$W_B = -32.47501 \text{ kJ}$$
$$W_{atm} = p_0\left(V_4 - V_3\right) = 100\left(1.53457 - 3.09132\right) = -155.675 \text{ kJ}$$
$$W_U = -32.47501 + 155.675 = +123.199 \text{ kJ}$$

Boundary work during compression process: process 4-1

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$W_B = -250.7776 \text{ kJ}$$
$$W_{atm} = p_0\left(V_1 - V_4\right) = 100\left(0.08636 - 1.53457\right) = -144.821 \text{ kJ}$$
$$W_U = -250.7776 + 144.821 = -105.9566 \text{ kJ}$$

Boundary work during heat addition and expansion process: 1-2

$$W_U = \left(W_B - W_{atm}\right)$$
$$W_B = 102.82161 \text{ kJ}$$
$$W_{atm} = p_0\left(V_2 - V_1\right) = 100\left(0.17397 - 0.08636\right) = 8.761 \text{ kJ}$$
$$W_U = 102.82161 - 8.761 = 94.06061 \text{ kJ}$$

Boundary work during expansion process: 2-3

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$W_B = 250.7776 \text{ kJ}$$
$$W_{atm} = p_0\left(V_3 - V_2\right) = 100\left(3.09132 - 0.17397\right) = 291.735 \text{ kJ}$$
$$\Delta\Phi = 250.7776 - 291.735 = -40.9574 \text{ kJ}$$

(b) Exergy supplied by the reservoir at 1048 K,

$$Q_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 102.82161 \times (1\text{-}\frac{298\text{K}}{1048\text{K}}) = 73.584 \text{ kJ}$$

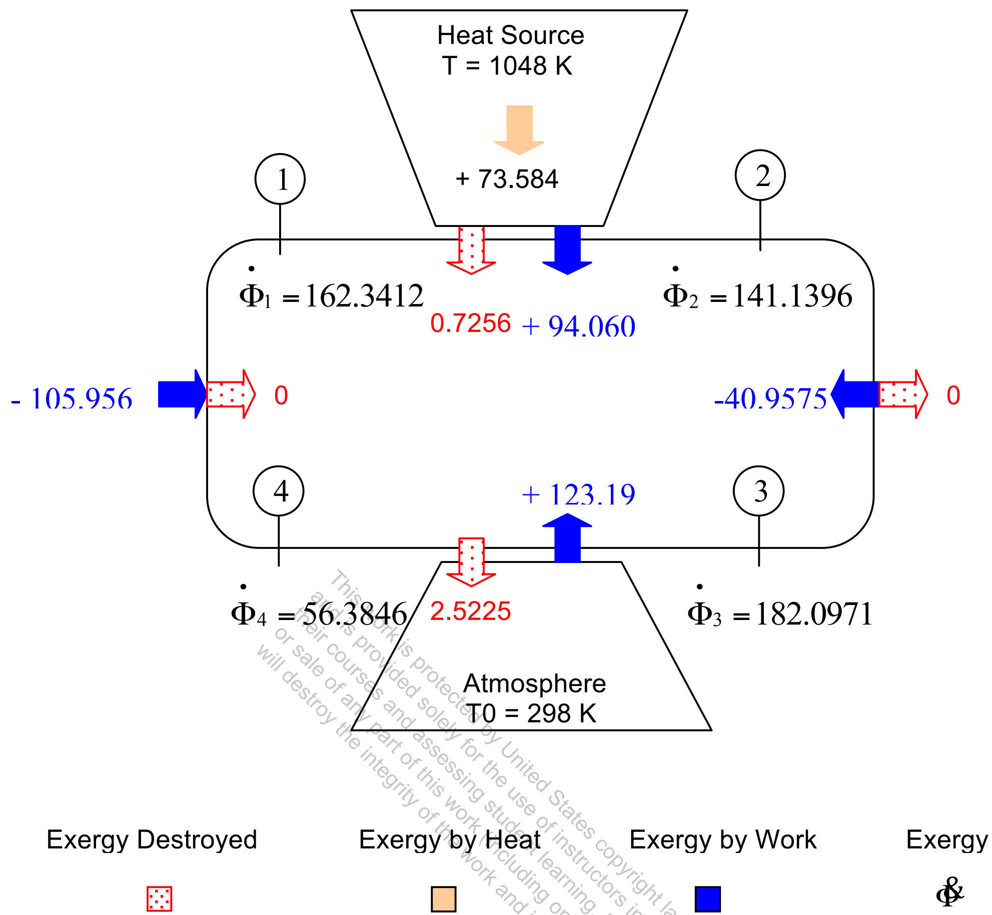
To calculate the exergetic efficiency, η_{II},

W_{net} = 70.3466 kJ

Wmax = Wnet + Total Exergy Destroyed

Wmax = 73.584 kJ

$$\eta_{II} = \frac{W_{net}}{\dot{W}_{\max}} = \frac{70.3466 \text{ kJ}}{73.584 \text{ kJ}} = 0.9560 = 95.60\%$$



Part a: Exergy Diagram for Carnot Cycle (*on kJ basis*)

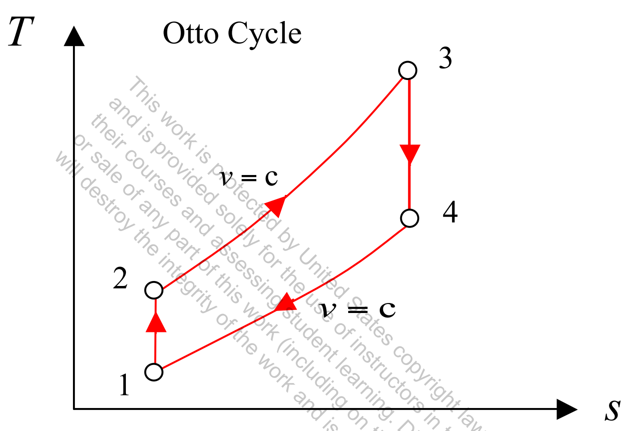
TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

7-6-3 [OGJ] In problem 7-3-2 [OIW], (a) perform a complete exergy inventory and draw an exergy flow diagram for the cycle on unit mass basis (kJ/kg). Assume the heat addition to take place from a reservoir at 1500°C and heat rejection to the atmosphere at 100 kPa, 25°C. Use the PG model for air. (b) What is the overall exergetic efficiency of the engine?

Analysis:

Heat Source at 1773 K (1500 °C)

Dead State: P0 = 100 kPa and T0 = 25 °C (298 K)



Given:
Specific, Reciprocating Cycle, PG Model
Assume, Mass = 1 kg and Volume = 1 m^3

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in air-standard Otto cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**298**	0	6.8866	0
State 1	85.5	**298**	1.09594	6.9314	0
State 2	1574	685	191.301	**6.9314**	388.93
State 3	2923	**1273**	480.006	7.3747	978.40
State 4	158.8	553	51.9106	**7.3747**	256.29

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression	A	190.205	-190.205	-87.5	-277.7052	0	0	0
Heat Addition	B	288.705	0	0	0	350.147	61.4428	17.54
Expansion	C	428.095	+428.095	+87.5	+515.5957	0	0	0
Heat Rejection	D	50.8147	0	0	0	0	50.8147	14.51
Total Cycle			237.89		237.89	350.147	122.257	32.05

Rate Calculations:

Boundary work during compression process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = -190.205 \text{ kJ}$$
$$W_{atm} = p_0\left(V_2 - V_1\right) = 100\left(0.125 - 1.0\right) = -87.5 \text{ kJ}$$
$$W_B = -190.205 - 87.5 = -277.70 \text{ kJ}$$

Boundary work during expansion process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = 428.095 \text{ kJ}$$
$$W_{atm} = p_0\left(V_4 - V_3\right) = 100\left(1.0 - 0.125\right) = 87.5 \text{ kJ}$$
$$W_B = 428.095 + 87.5 = 515.59 \text{ kJ}$$

(b) Exergy supplied by the reservoir at 1773 K,

$$Q_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 420.8896 \times (1\text{-}\frac{298\text{K}}{1773\text{K}}) = 350.14786 \text{ kJ}$$

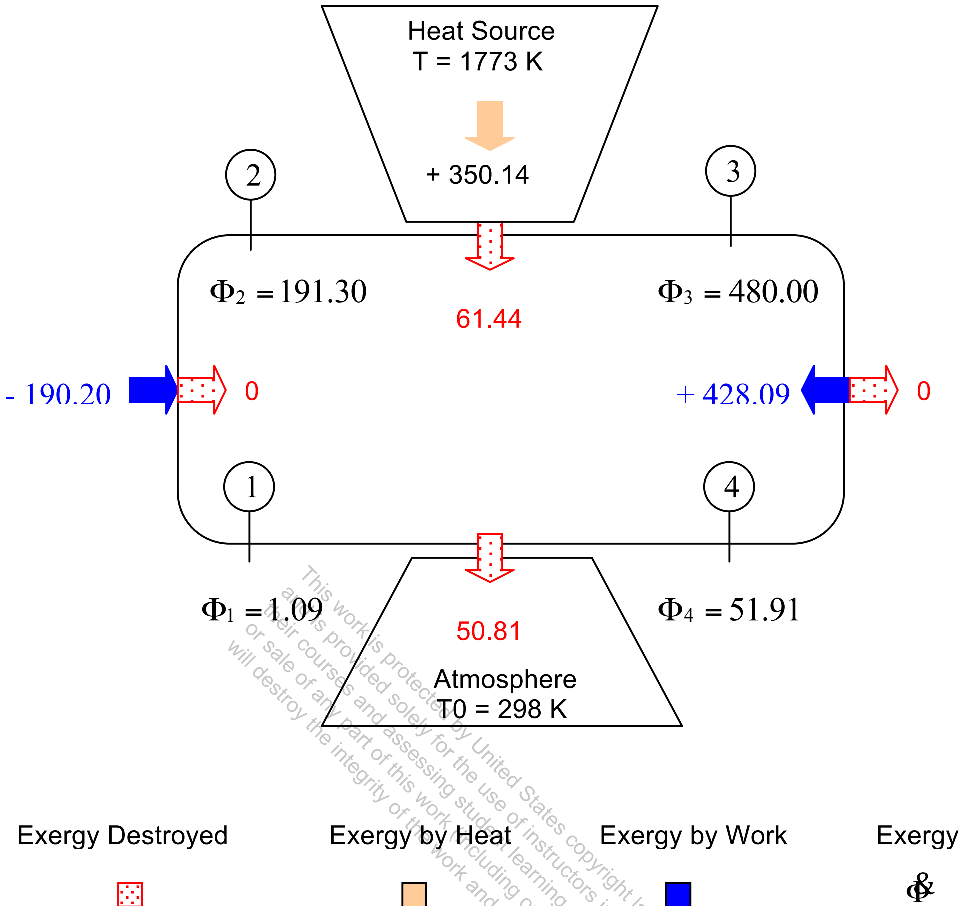
To calculate the exergetic efficiency, η_{II},

$$W_{net} = 237.89 \text{ kJ}$$

Wmax = Wnet + Total Exergy Destroyed

Wmax = 350.1478 kJ

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{237.89 \text{ kJ}}{350.14 \text{ kJ}} = 0.6794 = 67.94\%$$



Part a: Exergy Diagram for Otto Engine (*on kJ basis*)

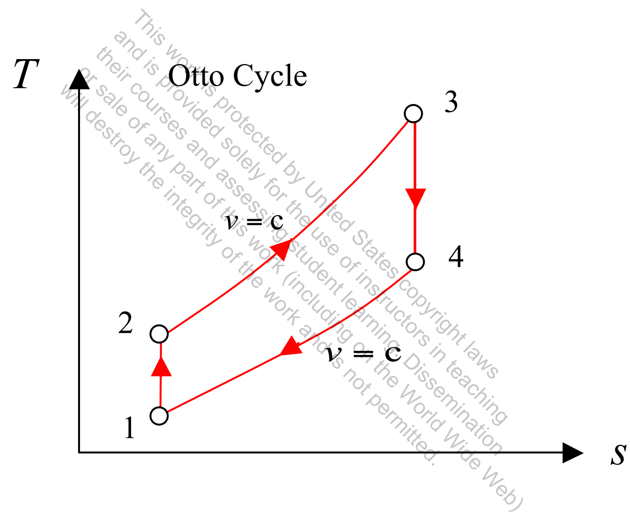
TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

7-6-4 [OZO] A four-stroke IC engine with 4 cylinders operates at 3000 rpm in an air-standard Otto cycle. Data for a single cylinder are given as follows. The compression ratio is 8.7. Prior to the isentropic compression process, air is at the atmospheric conditions of 100 kPa, 20°C and 660 cm^3. The temperature at the end of the isentropic expansion process is 810 K. Assume the heat addition to take place from a reservoir at 1827°C and heat rejection to the atmosphere. Using the PG model, (a) perform a complete exergy inventory and draw the exergy flow diagram on a rate (kW) basis. Determine (b) the overall exergetic efficiency and (c) the thermal (energetic) efficiency (η_{th}) of the cycle.

Analysis:

Heat Source at 2100 K (1827 °C)

Dead State: P0 = 100 kPa and T0 = 20 °C (293 K)



Given:
Specific, Reciprocating Cycle, PG Model
IC engine, 4-cylinder, 3000 rpm

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in air-standard Otto cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**293**	0	6.8697	-5.01747
State 1	**100**	**293**	0	6.8697	-5.01747
State 2	2069	697	0.16874	**6.8697**	400.5138
State 3	5717	1926	0.69228	**7.59744**	1634.1581
State 4	276	**810**	0.12304	7.59744	513.6384

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression	A	0.16874	-0.16874	-0.0584	-0.22716	0	0	0
Heat Addition	B	0.52354	0	0	0	0.5946	0.07106	12
Expansion	C	0.5692	+0.5692	+0.0584	+0.62765	0	0	0
Heat Rejection	D	0.12304	0	0	0	0	0.12304	20.7
Total Cycle			0.4005		0.4005	0.5946	0.1941	32.64
Engine kW			40.05		40.05	59.46	19.41	32.64

Rate Calculations:

Exergy change during different processes:

5) Compression process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_1 - \Phi_2) = 4\times\frac{3000}{2\times 60}\times(0-0.16770) = -16.87 \text{ kW}$$

6) Heat addition process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_3 - \Phi_2) = 4\times\frac{3000}{2\times 60}\times(0.68831-0.16770) = 52.35 \text{ kW}$$

7) Expansion process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_3 - \Phi_4) = 4\times\frac{3000}{2\times 60}\times(0.68831-0.12234) = 56.92 \text{ kW}$$

8) Heat rejection process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_1 - \Phi_4) = 4\times\frac{3000}{2\times 60}\times(0.16770-0.12234) = -12.30 \text{ kW}$$

Boundary work during compression process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = -0.1687 \text{ kJ}$$
$$W_{atm} = p_0\left(V_2 - V_1\right) = 100\left(0.00066 - 0.0000759\right) = -0.0584 \text{ kJ}$$
$$W_B = -0.1687 - 0.0584 = -0.2271 \text{ kJ}$$

Boundary work during compression process for an engine:

$$\dot{W}_B = -22.71 \text{ kW}$$

Boundary work during expansion process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = 0.5692 \text{ kJ}$$
$$W_{atm} = p_0\left(V_4 - V_3\right) = 100\left(0.00066 - 0.00007586\right) = 0.0584 \text{ kJ}$$
$$W_B = 0.5692 + 0.0584 = 0.6277 \text{ kJ}$$

Boundary work during expansion process for an engine:

$\dot{W}_B = 62.77 \text{ kW}$

(b) Exergy supplied by the reservoir at 2100 K,

$$Q_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 0.69102 \times (1 - \frac{293\text{K}}{2100\text{K}}) = 0.5946 \text{ kJ}$$

Exergy supplied for an engine = 59.46 kW

To calculate the exergetic efficiency, η_{II},

$W_{net} = 40.05 \text{ kW}$

Wmax = Wnet + Total Exergy Destroyed

Wmax = 59.46 kW

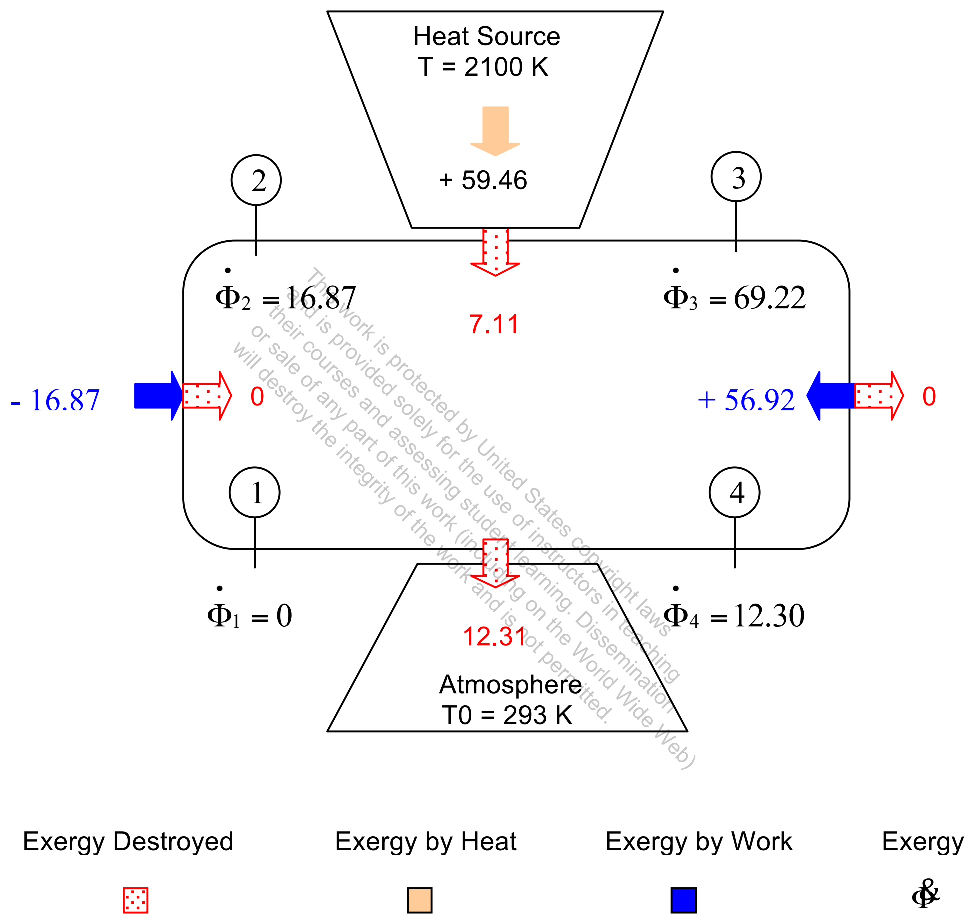
$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{40.05 \text{ kW}}{59.46 \text{ kW}} = 0.6735 = 67.35\%$$

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

$\dot{W}_{net} = 40.05 \text{ kW}$

$\dot{Q}_{in} = 69.10 \text{ kW}$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{40.05 \text{ kW}}{69.10 \text{ kW}} = 0.5795 = 57.95\%$$



Part a: Exergy Diagram for Otto Engine (*on kW basis*)

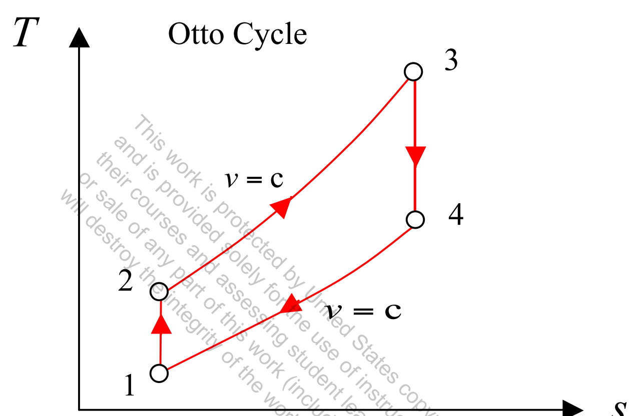
TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

7-6-5 [OGW] For each process in problem 7-3-15 [OLK] , (a) develop an exergy inventory on a rate basis (in kW) and draw an exergy flow diagram for the cycle, and (b) determine the exergetic efficiency of the engine. Assume the heat addition and heat rejection to take place with reservoirs at the maximum and minimum temperature of the cycle respectively.

Analysis:

Heat Source at 1773 K (1500 °C)

Dead State: P0 = 100 kPa and T0 = 25 °C (298 K)



Given:
Specific, Reciprocating Cycle, PG Model
IC engine, single-cylinder, 300 rpm, Bore-12 cm and Stroke-50 cm

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in air-standard Otto cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**298**	0	6.8866	0
State 1	**100**	**298**	0	6.8866	0
State 2	892	557	0.988045	**6.8866**	260.20
State 3	2197	**1373**	4.264862	7.53262	1078.75
State 4	246	734	1.003557	**7.53262**	438

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression	A	0.98804	-0.98804	-0.5655	-1.55353	0	0	0
Heat Addition	B	3.27682	0	0	0	4.06576	0.78894	19.40
Expansion	C	3.26130	+3.26130	+0.5655	+3.8268	0	0	0
Heat Rejection	D	1.00355	0	0	0	0	1.00355	24.68
Total Cycle			2.27327		2.27327	4.06576	1.79249	44.09
Engine kW			5.68317		5.68317	10.1644	4.6185	44.09

Rate Calculations:

Exergy change during different processes:

1) Compression process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_1 - \Phi_2) = 1\times\frac{300}{2\times 60}\times(0-0.988045) = -2.4701 \text{ kW}$$

2) Heat addition process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_3 - \Phi_2) = 1\times\frac{300}{2\times 60}\times(4.2648626-0.988045) = 8.192044 \text{ kW}$$

3) Expansion process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_3 - \Phi_4) = 1\times\frac{300}{2\times 60}\times(4.2648626-1.00355746) = 8.1532628 \text{ kW}$$

4) Heat rejection process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_1 - \Phi_4) = 1\times\frac{300}{2\times 60}\times(0-1.00355746) = -2.50889365 \text{ kW}$$

Boundary work during compression process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = -0.98804 \text{ kJ}$$
$$W_{atm} = p_0\left(V_2 - V_1\right) = 100\left(0.0015 - 0.0071548666\right) = -0.56548666 \text{ kJ}$$
$$W_B = -0.98804 - 0.56548666 = -1.55353 \text{ kJ}$$

Boundary work during compression process for an engine:

$$\dot{W}_B = -3.883825 \text{ kW}$$

Boundary work during expansion process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = 3.26130 \text{ kJ}$$
$$W_{atm} = p_0\left(V_4 - V_3\right) = 100\left(0.0071548666 - 0.0015\right) = 0.5655$$
$$W_B = 3.26130 + 0.5655 = 3.8268 \text{ kJ}$$

Boundary work during expansion process for an engine:

$\dot{W}_B = 9.567$ kW

(b) Exergy supplied by the reservoir at 1773 K,

$$Q_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 4.88719 \times (1 - \frac{298\text{K}}{1773\text{K}}) = 4.06576 \text{ kJ}$$

Exergy supplied for an engine = 10.1644 kW

To calculate the exergetic efficiency, η_{II},

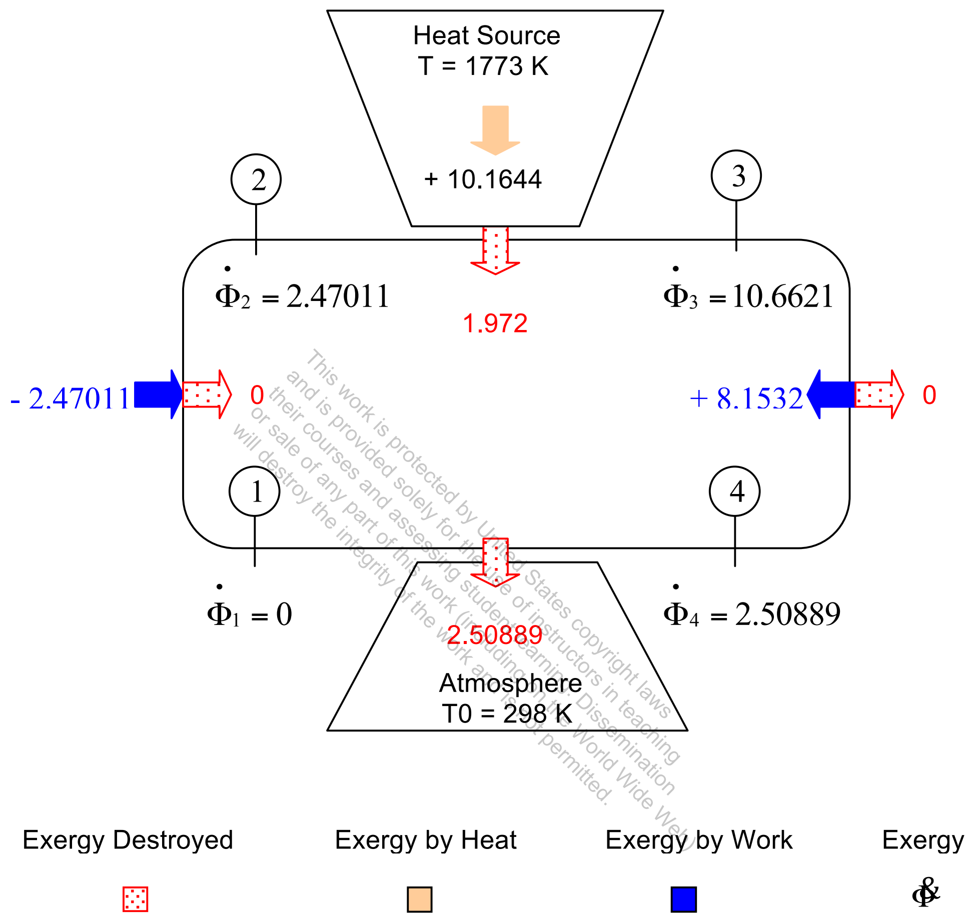
$W_{net} = 5.68317$ kW
Wmax = Wnet + Total Exergy Destroyed
Wmax = 10.1644 kW

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{5.68317 \text{ kW}}{10.1644 \text{ kW}} = 0.5591 = 55.91\%$$

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

$\dot{W}_{net} = 5.68317$ kW
$\dot{Q}_{in} = 12.217975$ kW

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{5.68317 \text{ kW}}{12.21797 \text{ kW}} = 0.4651 = 46.51\%$$



Part a: Exergy Diagram for Otto Engine (*on kW basis*)

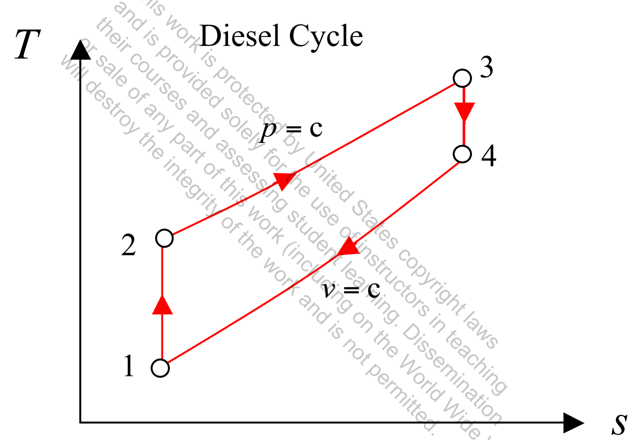
TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

7-6-6 [OZR] A four cylinder, four-stroke 3-L (maximum volume per cylinder) diesel engine that operates at 1500 rpm on an ideal Diesel cycle has a compression ratio of 18 and a cutoff ratio of 3. Air is at 25°C and 100 kPa (atmospheric conditions) at the beginning of the compression process. Assume heat addition takes place from a reservoir at 2600°C and heat rejection to the atmosphere. Using the PG model, (a) perform a complete exergy inventory and draw the exergy flow diagram on a rate (kW) basis. Determine (b) the overall exergetic efficiency and (c) the thermal (energetic) efficiency (η_{th}) of the cycle.

Analysis:

Heat Source at 2873 K (2600 °C)

Dead State: P0 = 100 kPa and T0 = 25 °C (298 K)



Given:
Specific, Reciprocating Cycle,
Diesel engine, Four-cylinder, Compression ratio-18 and Cutoff ratio-3

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in Diesel cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**298**	0	6.8866	0
State 1	**100**	**298**	0	6.8866	0
State 2	5729	949	1.35142	**6.8866**	653
State 3	**5729**	2847	4.99982	7.9891	2557
State 4	466	1389	1.58759	**7.9891**	1094

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression	A	1.35142	-1.35142	-0.28334	-1.63476	0	0	0
Heat Addition	B	3.6484	+1.87621	+0.03335	+1.90956	5.9845	0.45989	7.68
Expansion	C	3.41223	+3.41223	+0.2499	+3.66222	0	0	0
Heat Rejection	D	1.58759	0	0	0	0	1.58759	26.52
Total Cycle			3.93702		3.93702	5.9845	2.01413	34.21
Engine kW			196.851		196.851	299.225	102.374	34.21

Rate Calculations:

Exergy change during different processes:

1) Compression process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_1 - \Phi_2) = 4\times\frac{1500}{2\times 60}\times(0-1.35142) = -67.571 \text{ kW}$$

2) Heat addition process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_3 - \Phi_2) = 4\times\frac{1500}{2\times 60}\times(4.99982-1.35142) = 182.42 \text{ kW}$$

3) Expansion process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_3 - \Phi_4) = 4\times\frac{1500}{2\times 60}\times(4.99982-1.58759) = 170.61 \text{ kW}$$

4) Heat rejection process:

$$\Delta\dot{\Phi} = n_{cyl}\frac{N}{2}(\Phi_1 - \Phi_4) = 4\times\frac{1500}{2\times 60}\times(0-1.58759) = -79.3795 \text{ kW}$$

Boundary work during compression process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$

$$\Delta\Phi = -1.35142 \text{ kJ}$$

$$W_{atm} = p_0\left(V_1 - V_2\right) = 100\left(0.0030 - 1.7E-4\right) = -0.283 \text{ kJ}$$

$$W_B = -1.35142 - 0.28334 = -1.63476 \text{ kJ}$$

Boundary work during compression process for an engine:

$$\dot{W}_B = -81.738 \text{ kW}$$

Boundary work during heat addition process:

$$W_U = \left(W_B - W_{atm}\right)$$
$$W_B = 1.90956 \text{ kJ}$$
$$W_{atm} = p_0\left(V_3 - V_2\right) = 100\left(5.0E-4-1.7E-4\right) = 0.0335 \text{ kJ}$$
$$W_U = 1.90956 - 0.0335 = 1.87621 \text{ kJ}$$

Boundary work during heat addition process for an engine:

$$\dot{W}_B = 93.8105 \text{ kW}$$

Boundary work during expansion process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = 3.41223 \text{ kJ}$$
$$W_{atm} = p_0\left(V_4 - V_3\right) = 100\left(0.0030-5.0E-4\right) = 0.25$$
$$W_B = 3.41223 + 0.25 = 3.662 \text{ kJ}$$

Boundary work during expansion process for an engine:

$$\dot{W}_B = 183.115 \text{ kW}$$

(b) Exergy supplied by the reservoir at 2873 K,

$$Q_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 6.67706 \times (1\text{-}\frac{298\text{K}}{2873\text{K}}) = 5.9845 \text{ kJ}$$

Exergy supplied for an engine = 299.225 kW

To calculate the exergetic efficiency, η_{II} ,

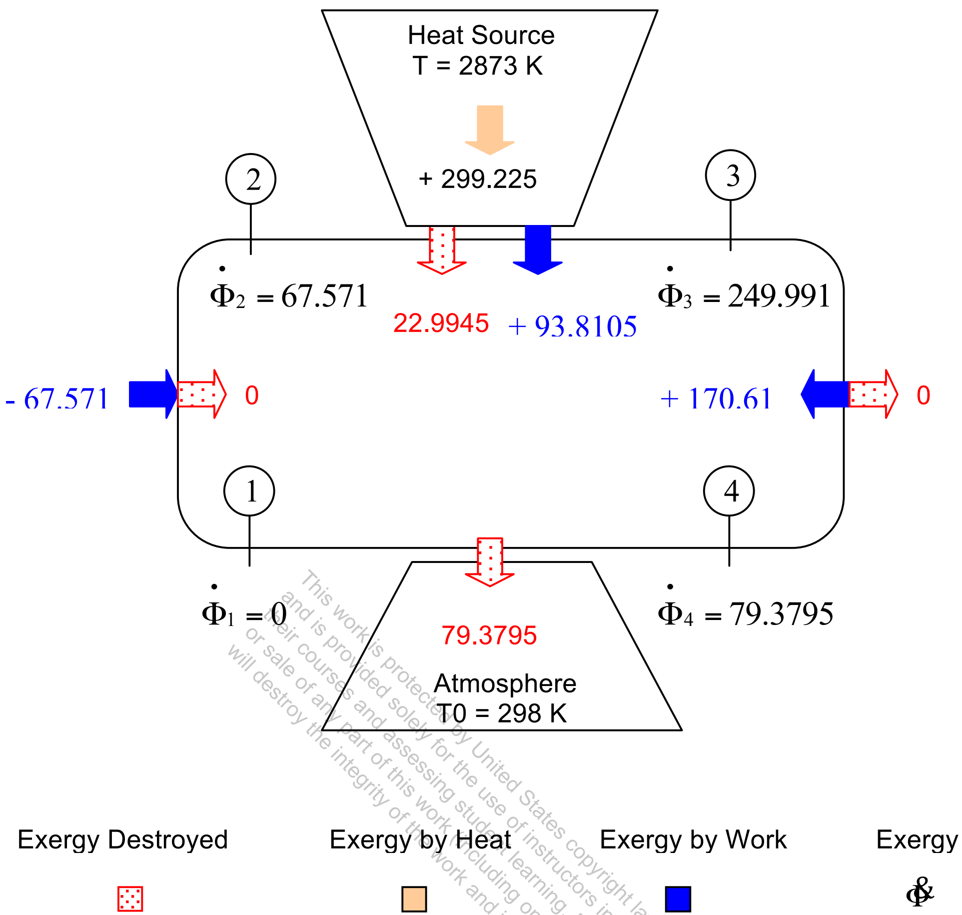
$W_{net} = 196.851 \text{ kW}$
Wmax = Wnet + Total Exergy Destroyed
Wmax = 299.225 kW

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{196.851 \text{ kW}}{299.225 \text{ kW}} = 0.6578 = 65.78\%$$

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

$\dot{W}_{net} = 196.851 \text{ kW}$
$\dot{Q}_{in} = 333.853 \text{ kW}$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{196.851 \text{ kW}}{333.853 \text{ kW}} = 0.5896 = 58.96\%$$



Part a: Exergy Diagram for Diesel Engine (*on kW basis*)

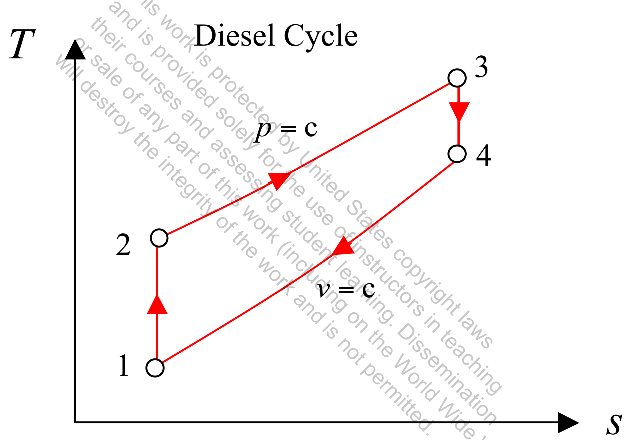
TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-cycle TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

7-6-7 [OZB] In problem 7-4-15 [OGR] assume that heat is added from a reservoir at 1800°C and the atmospheric conditions are 100 kPa and 20°C. (a) Determine the process that carries the biggest penalty in terms of exergy destruction. (b) Also develop a balance sheet for exergy for the entire cycle on a rate (kW) basis, including an exergy flow diagram.

Analysis:

Heat Source at 2973 K (2700 °C)

Dead State: P0 = 100 kPa and T0 = 20 °C (293 K)



Given:
Specific, Reciprocating Cycle,
Diesel engine, Compression ratio-19
Assume m=1 kg

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in Diesel cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**293**	0	6.8697	-5.01747
State 1	**105**	**293**	0.09853	6.8557	-5.01747
State 2	6488	953	397.266	**6.8557**	657.541
State 3	**6488**	2946	1502.18	7.9879	2657
State 4	510	1423	478.139	**7.9879**	1129.36

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression	A	397.167	-397.167	-75.908	-473.075	0	0	0
Heat Addition	B	1104.91	+563.158	+8.816	+571.97	1802.89	134.822	7.47
Expansion	C	1024.04	+1024.04	+67.0983	+1091.13	0	0	0
Heat Rejection	D	478.139	0	0	0	0	478.139	26.52
Total Cycle			1190.03		1190.03	1802.89	612.86	33.99

Rate Calculations:

Boundary work during compression process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = -397.167 \text{ kJ}$$
$$W_{atm} = p_0\left(V_1 - V_2\right) = 100\left(0.04217 - 0.80124\right) = -0.75908 \text{ kJ}$$
$$W_B = -397.167 - 0.75908 = -473.074 \text{ kJ}$$

Boundary work during heat addition process:

$$W_U = \left(W_B - W_{atm}\right)$$
$$W_B = 571.9746 \text{ kJ}$$
$$W_{atm} = p_0\left(V_3 - V_2\right) = 100\left(0.13033 - 0.04217\right) = 8.816 \text{ kJ}$$
$$W_U = 571.9746 - \ 8.816 = 563.1586 \text{ kJ}$$

Boundary work during expansion process:

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = 1024.04 \text{ kJ}$$
$$W_{atm} = p_0\left(V_4 - V_3\right) = 100\left(0.80124 - 0.13033\right) = 67.098$$
$$W_B = 1024.04 + 67.098 = 1091.13 \text{ kJ}$$

(b) Exergy supplied by the reservoir at 2873 K,

$$Q_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 2000 \times (1\text{-}\frac{293\text{K}}{2973\text{K}}) = 1802.89 \text{ kJ}$$

To calculate the exergetic efficiency, η_{II},

$W_{net} = 1190.03$ kJ

Wmax = Wnet + Total Exergy Destroyed

Wmax = 1802.89 kJ

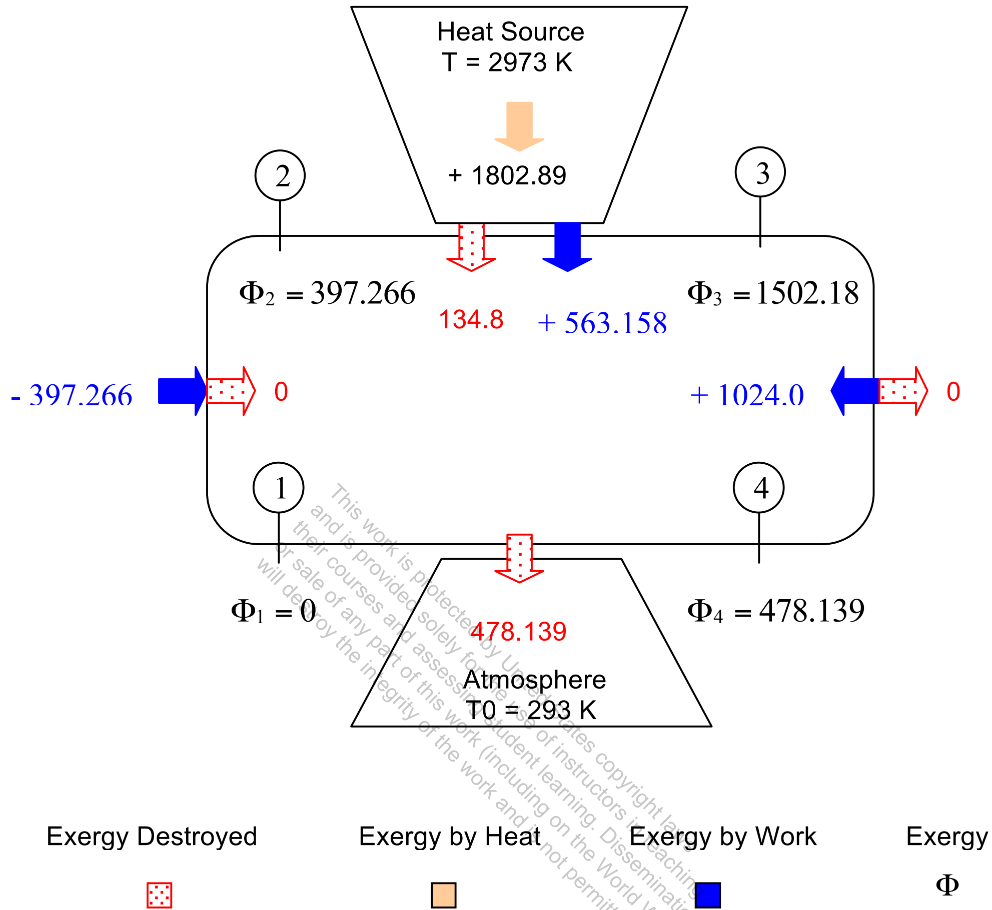
$$\eta_{II} = \frac{W_{net}}{W_{\max}} = \frac{1190.03 \text{ kJ}}{1802.89 \text{ kJ}} = 0.66 = 66\%$$

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

$W_{net} = 1190.03$ kJ

$Q_{in} = 2000$ kJ

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{1190.03 \text{ kJ}}{2000 \text{ kJ}} = 0.5950 = 59.50\%$$



Part a: Exergy Diagram for Diesel Cycle (*on kJ basis*)

TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-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.

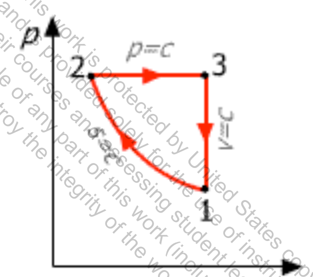
In test solution P1=p1 and T1=T1 is taken instead of P1=P0 and T1=T0

7-6-8 [OZS] In problem 7-5-8 [OGL] assume that heat is added from a reservoir at 2000°C and the atmospheric conditions are 100 kPa and 27°C. Determine (a) the thermal efficiency (η_{th}) and (b) exergetic efficiency of the cycle. (c) Also develop a balance sheet for exergy for the entire cycle on unit mass (kJ/kg) basis complete with an exergy flow diagram.

Analysis:

Heat Source at 2273 K (2000 °C)

Dead State: P0 = 100 kPa and T0 = 27 °C (300 K)



Given:
Specific, Air Standard Cycle,

Spreadsheet Calculation:

Table 1, Property values, exergy flows and entropy production rates at various state points in cycle at rated conditions

	Pressure kPa	Temperature K	Exergy kJ $\Phi = m \times \phi$	Entropy kJ/kg.K	Enthalpy kJ/kg
State 0	**100**	**300**	0	6.8934	2.006
State 1	**100**	**300**	0	6.8934	2.006
State 2	**700**	524	95.4549	**6.8934**	226.26
State 3	**700**	2101	871.871	8.2876	1809

Note: Blue quantities are given and Black quantities are calculated using TEST.

Table 2, Change in Exergy, Actual Work, Exergy Supplied, Exergy Destroyed in various processes of cycle.

Process	Device	Exergy Change $\Delta\Phi$ kJ	W_U kJ	W_{atm} kJ	W_B $(W_U + W_{atm})$ kJ	Exergy Supplied from Reservoir kJ	Exergy Destroyed kJ	Exergy Destroyed %
Compression	A	95.4549	-95.4549	-64.6711	-160.1260	0	0	0
Heat Addition	B	776.416	388.026	64.6711	+452.6979	1374.00	209.564	15.25
Heat Rejection	C	871.871	0	0	0	0	871.871	63.45
Total Cycle			292.571		292.571	1374.00	1081.42	78.70

Rate Calculations:

Boundary work during compression process: 1-2

$$\Delta\Phi = W_U = \left(W_B - W_{atm}\right)$$
$$\Delta\Phi = -95.4549 \text{ kJ}$$
$$W_{atm} = p_0\left(V_2 - V_1\right) = 100\left(0.21468 - 0.86139\right) = -64.671 \text{ kJ}$$
$$W_B = -95.4549 - 64.671 = -160.12 \text{ kJ}$$

Boundary work during heat addition process:2-3

$$W_U = \left(W_B - W_{atm}\right)$$
$$W_B = 452.6979 \text{ kJ}$$
$$W_{atm} = p_0\left(V_3 - V_2\right) = 100\left(0.86139 - 0.21468\right) = 64.671 \text{ kJ}$$
$$W_U = 452.6979 - 64.671 = 388.0269 \text{ kJ}$$

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

$$\dot{W}_{net} = 292.571 \text{ kJ}$$
$$\dot{Q}_{in} = 1582.93 \text{ kJ}$$
$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{292.571 \text{ kJ}}{1582.93 \text{ kJ}} = 0.1848 = 18.48\%$$

(b) Exergy supplied by the reservoir at 2273 K,

$$Q_{\text{in}} \times (1 - \frac{T_o}{T_R}) = 1582.9302 \times (1\text{-}\frac{300\text{K}}{2273\text{K}}) = 1374.0 \text{ kJ}$$

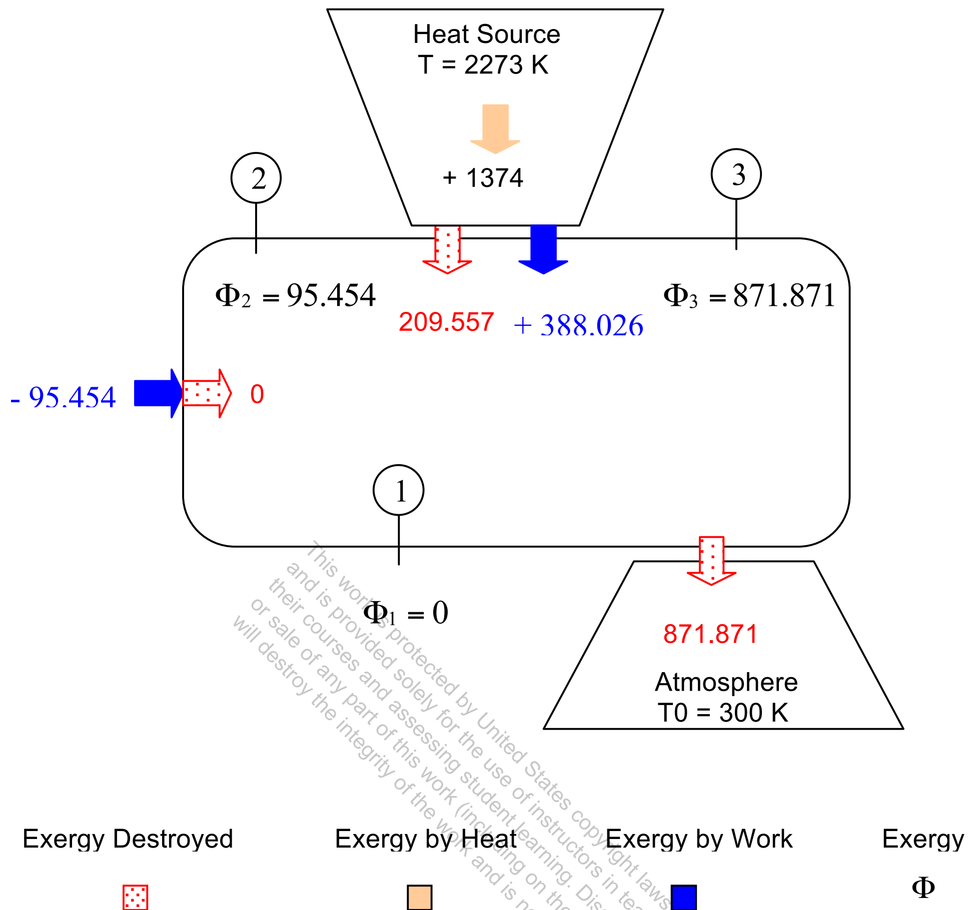
To calculate the exergetic efficiency, η_{II},

$$W_{net} = 292.571 \text{ kJ}$$

Wmax = Wnet + Total Exergy Destroyed

Wmax = 1374 kJ

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{W}_{\max}} = \frac{292.571 \text{ kJ}}{1374 \text{ kJ}} = 0.2129 = 21.29\%$$



Part C: Exergy Diagram for Diesel Engine (*on kJ basis*)

TEST Solution Use the PG (or IG based on problem statement) reciprocating closed-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.