THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

83-JPGC-GT-3

COMBINED CYCLE AND WASTE HEAT RECOVERY POWER SYSTEMS BASED ON A NOVEL THERMODYNAMIC ENERGY CYCLE UTILIZING LOW-TEMPERATURE HEAT FOR POWER GENERATION

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ABSTRACT

A new thermodynamic energy cycle has been developed, using a multicomponent working agent. Condensation is supplemented with absorption, following expansion in the turbine. Several combined power systems based on this cycle have been designed and cost-estimated. Efficiencies of these new systems are 1.35 to 1.5 times higher than the best Rankine Cycle system, at the same border conditions. Investment cost per unit of power output is about two-thirds of the cost of a comparable Rankine Cycle system. Results make cogeneration economically attractive at current energy prices. The first experimental installation is planned by Fayette Manufacturing Company and Detroit Diesel Allison Division of General Motors.

Cogeneration of electricity by means of waste-heat recovery is undisputably one of the biggest potentials in energy conservation. Motivated by government subsidies, an intensive development of waste-heat recovery systems, using variations of the century-old Rankine Cycle technology, has been directed toward improvement of the mechanical components of the system. As a result, very refined, but expensive, components have been developed. However, these waste-heat recovery systems are not economically feasible at this time. At current prices of prime energy and electricity, the specific cost per installed unit of power of such systems must be reduced by twenty-five percent to make Rankine Cycle systems economically feasible. It is easy to demonstrate that such an improvement cannot be achieved by merely improving the equipment comprising such systems. It is generally agreed that such systems will become economically feasible if and when prices of electricity increase significantly in relation to equipment investment costs.

Exergy, Inc. has developed a new energy system, based on a new thermodynamic cycle, using low-temperature heat as an energy source. The result is a new patented cycle and system that make it economically feasible at current energy prices. In distinction from the Rankine Cycle, this cycle which is named the Texergy Cycle includes a distillation subsystem and substitutes absorption of the working fluid for condensation following expansion in the turbine. A multi-component working fluid is used in this system, which permits effective utilization of a variable-temperature heat typical of waste-heat sources.

To demonstrate the advantages of the new cycle, systems were developed using waste heat from a DeLaval diesel engine DSRV-12-4, with a net power output of 5,217 KW. Waste heat available from this engine is tabulated in Table 1. Power Systems Engineering, Inc. (Houston, Texas) developed a Rankine Cycle system using this waste heat, which was optimized using computer programs. The maximum energy output of the optimized Rankine Cycle system is 577.4 KW, with an approximate installed cost of $2,200 per KW. Using the same waste-heat source, two variants of the Texergy Cycle System were developed. The first system is presented in Figure 1, and works as follows: An initial mixture of water-ammonia is pumped to an intermediate pressure and divided into two streams. The larger stream is sent into a heat exchanger, partially evaporated, and flashed into a liquid and a vapor stream. The vapor is then recombined with the smaller of the two streams. This enriched mixture is condensed, pumped to the desired working pressure, and completely evaporated, using waste heat from the diesel-engine exhaust gases. The steam produced is expanded through the turbine, and directed in counterflow into a heat exchanger, where it is cooled, providing heat for partial evaporation in the distillation step of the process, as described above. The liquid produced in the flash distillation is throttled to turbine-discharge pressure, mixed with the partially condensed steam, discharged from the turbine, and cooled in heat exchanger and then completely condensed by the cooling water. This system based on use of Turbodyne EST turbine provides a net output of 730.3 kW. Another system, which utilizes waste heat both from exhaust gas and from jacket water and is based on radial inflow type turbine is presented in Figure 2. It differs from the first system in that it has two distillation steps. This latter system has a net output of 860.9 KW. Parameters of the working fluid at all key points of the process for each variant of the Texergy Cycle are presented in Table 2 and in Table 3. Thermodynamical data for water-ammonia mixture for pressures range up to 500 psia published by Institute of Gas Technology Research were used in calculations (1). Thermodynamical data for pressures higher than 500 psia were obtained from the computer data bank of Robinson & Associates LTD (Edmonton, Alberta, Canada).

The costs of both developed systems were estimated by Power Systems Engineering, Inc. The complete comparison of the Rankine Cycle System and both Texergy Cycle Systems is presented in Table 4. The Texergy Cycle Systems have significantly higher energy efficiencies, and significantly lower specific costs.

The design of power system based on presented cycle and using exhaust gas from 501-KB turbine of Detroit Diesel Allison Division of General Motors is being currently developed. The first result of this design has shown that from a flow of exhaust gas with initial temperature of $950^{0}F$ ($510^{0}C$) and a flow rate of 33 lbs/sec, (15 kg/sec) a net output of 1,370.2 kW was achieved. The Second Law efficiency of this system is 44.1%. This design was based on the use of Turbodyne EST turbine. Comparison of this design and above described designs demonstrates that Turbodyne EST turbine which has a limit of inlet pressure of 700 psig is not adequate to boarder conditions of heat source. It is expected that by using radial inflow type of turbine net output of approximately 1,550 KW will be acheived.

Due to the fact that different types of turbine with different efficiencies can be used in these systems, for a proper comparison of different systems, so called internal cycle thermodynamic efficiency which is the ratio of Second Law efficiency to the turbine adiabatic efficiency has to be used.

A system based on the presented cycle was also developed for geothermal application. This system provides net output 1.4 times higher than the Rankine Cycle System using the same heat source (2).

The higher thermodynamic reversibility, and consequently higher efficiency, of the Texergy Cycle as compared with the Rankine Cycle is due to two factors:

1) The multicomponent working fluid, having a variable boiling temperature, provides significantly lower energy losses in the evaporator, as the waste-heat source has a variable temperature in the evaporator as well.

2) The low-temperature part of the heat available is used, not for evaporation, but for distillation, which is thermodynamically more efficient.

The lower specific costs of the Texergy Cycle System are due to the fact that:

1) The working fluid starts to boil almost immediately after entering the evaporator, which increases the efficiency of the heat exchange.

2) The quantity of heat rejected in the condenser is significantly smaller than in the Rankine Cycle system, reducing the surface and cost of the condenser, as well as the cost of the cooling tower and auxiliary subsystems.

3) Higher efficiency of the Texergy Cycle system results in lower quantity of heat transferred in the evaporator per unit of power output and thus, in lower specific cost of evaporator.

Economic comparison of the Texergy Cycle with Rankine Cycle systems, based on 6¢/KWH price of electricity produced, shows that Texergy Cycle Systems provide a payout period of approximately three-and-one-half years versus six-and-one-half years for Rankine Cycle systems. Thus, Texergy Cycle Systems make cogeneration of electricity using waste-heat recovery economically feasible at current prices of fuel and electricity. Currently Fayette Manufacturing Company and Detroit Diesel Allision Division of General Motors are planning to build the first combined cycle installation using this new cycle for 501-KB turbine. Fluor Corporation is also planning to build a power system based on the presented cycle.

BIBLIOGRAPHY

1. Institute of Gas Technology Research Bulletin No. 34, 1976.

2. Barber-Nichols Engr. Co. "Final Design, Installation and Baseline Testing of 500 KW Direct Contact Pilot Plant at East Mesa", LBL-11153 UC-66d. May 1980.

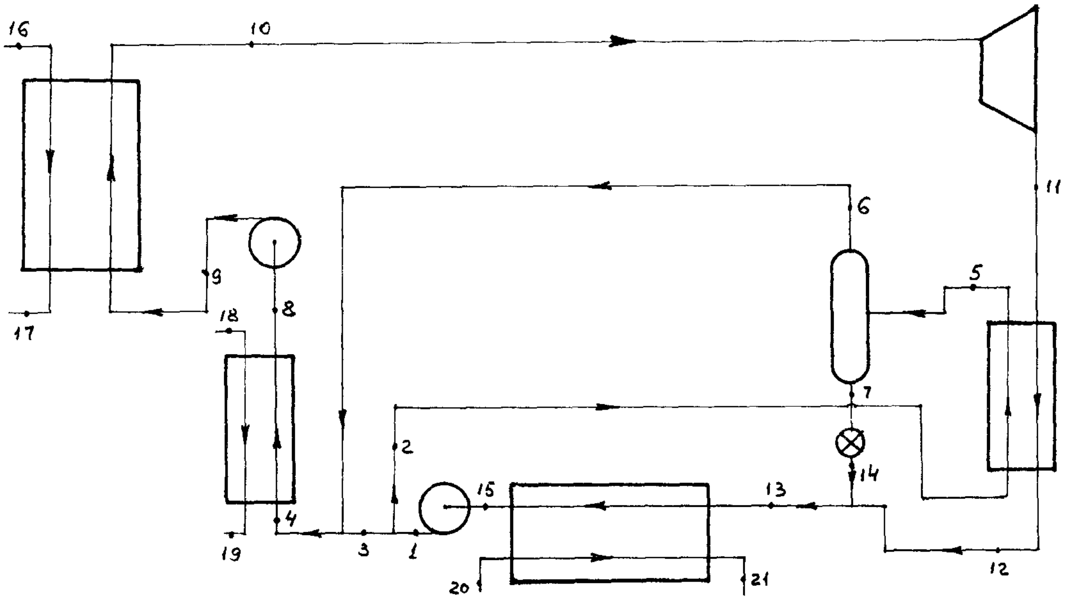

Figure 1. Texergy Cycle Power System with one distillation step.

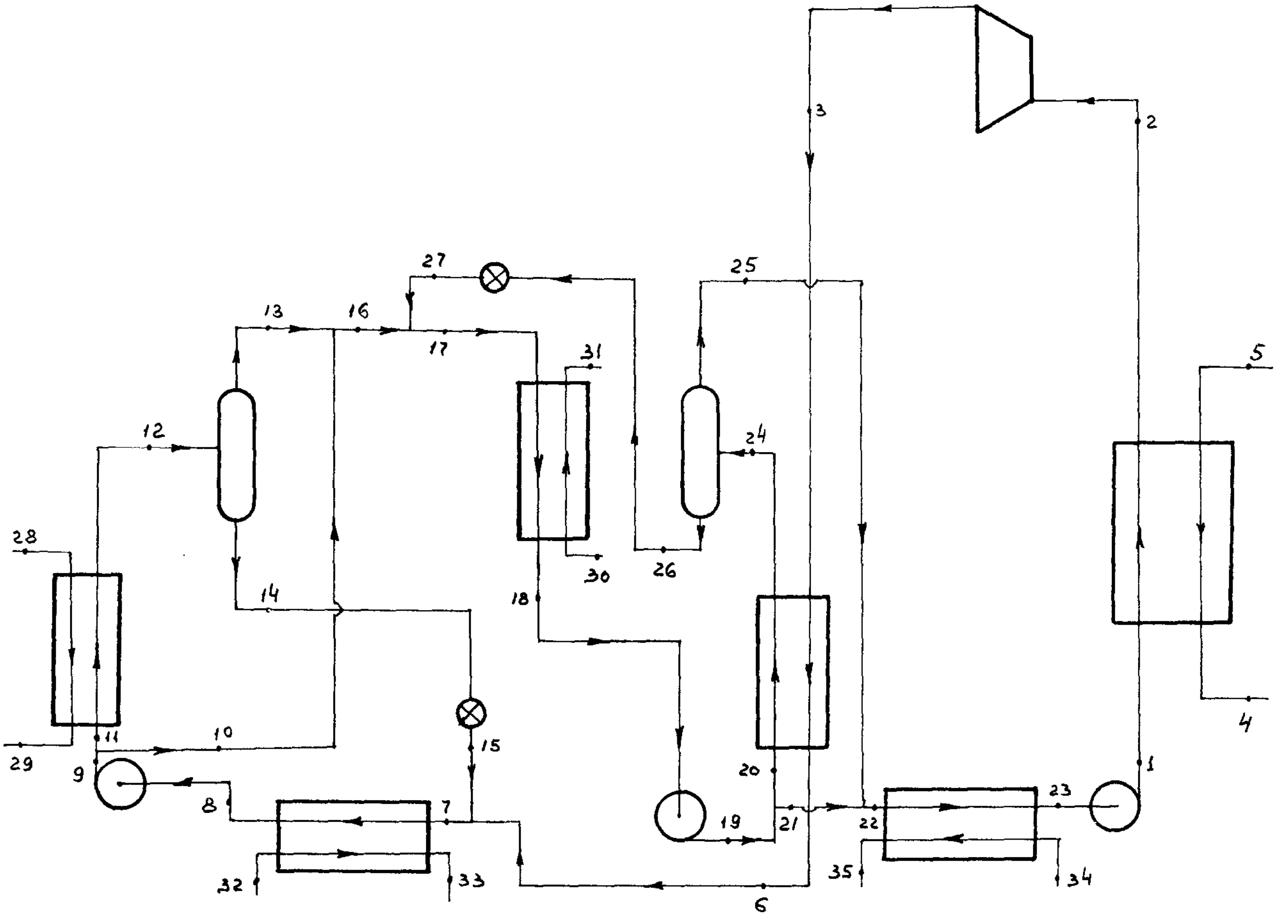

Figure 2. Texergy Cycle Power System with two distillation steps.

Table 1

Exergy potential of waste heat from DeLaval diesel engine DSRV-12-4

Source	Inlet Temperature		Outlet Temperature		Heat Flow Rate		Exergy
	^oF	^oC	^oF	^oC	$\frac{BTU}{hr}$	kW	kW
Exhaust gas	750	398.9	200	93.3	12,566,000	3,682.8	1,431.3
Jacket Water	175	79.4	163	72.8	8,044,300	2,357.6	277.9
Lubricating Oil	175	79.4	153	67.2	2,413,290	707.3	78.3
						TOTAL	1,787.5

Table 2

Point	Temperature		Pressure		Enthalpy		Concentration	Weight	
No.	^oF	^oC	psia	kPa	BTU/lb	KJ/kg	lb/lb or kg/kg	lb/hr	kg/hr
1	95	35.0	40.0	275.8	-15.0	-34.9	0.250	47,182	21,401
2	95	35.0	40.0	275.8	-15.0	-34.9	0.250	39,859	18,080
3	95	35.0	40.0	275.8	-15.0	-34.9	0.250	7,323	3,322
4	154	67.5	40.0	275.8	182.3	424.0	0.430	10,257	4,652
5	175	79.4	40.0	275.8	125.0	290.8	0.250	39,859	18,000
6	175	79.4	40.0	275.8	675.0	1,570.0	0.880	2,934	1,331
7	115	79.4	40.0	275.8	81.3	189.1	0.200	36,925	16,749
8	95	35.0	40.0	275.8	-35.0	-81.4	0.430	10,257	4,652
9	95	35.0	711.2	4,903.3	-35.0	-81.4	0.430	10,257	4,652
10	700	371.1	711.2	4,903.3	1,150.0	2,674.9	0.430	10,257	4,652
11	185	85.0	12.0	82.7	903.5	2,101.5	0.430	10,257	4,652
12	143	61.7	12.0	82.7	365.5	850.2	0.430	10,257	4,652
13	138	58.9	12.0	82.7	143.1	332.9	0.250	47,182	21,401
14	132	55.6	12.0	82.7	81.3	189.1	0.200	36,925	16,749
15	95	35.0	12.0	82.7	-15.0	-34.9	0.250	47,182	21,401
16	750	398.9	-	-	-	-	gas	91,386	41,452
17	218	103,3	-	-	-	-	gas	91,386	41,452
18	85	29.4	-	-	-	-	water	111,442	50,549
19	105	40.6	-	-	-	-	water	111,442	50,549
20	85	29.4	-	-	-	-	water	372,975	169,179
21	105	40.6	-	-	-	-	water	372,975	169,179

Table 3

1	95.0	35.0	995.60	6,864.4	34.2	79.6	0.50	12,015.2	5,450.0
2	608.0	320.0	995.60	6,864.4	1,080.0	2,512.1	0.50	12,015.2	5,450.0
3	174.2	79.0	14.22	98.1	831.4	1,933.8	0.50	12,015.2	5,450.0
4	200.0	93.3	-	-	-	-	gas	91,386.0	41,452.0
5	750.0	399.0	-	-	-	-	gas	91,386.0	41,452.0
6	138.2	59.0	14.22	98.1	492.3	1,145.1	0.50	12,015.2	5,450.0
7	140.0	60.0	14.22	98.1	229.5	533.8	0.26	38,228.2	17,340.9
8	95.0	35.0	14.22	98.1	21.2	49.3	0.26	38,228.2	17,340.9
9	95.0	35.0	28.45	196.1	21.2	49.3	0.26	38,228.2	17,340.9
10	95.0	35.0	28.45	196.1	21.2	49.3	0.26	6,676.2	3,027.8
11	95.0	35.0	28.40	196.1	21.2	49.3	0.26	31,555.0	14,313.1
12	167.0	75.0	28.45	196.1	234.0	544.3	0.26	31,555.0	14,313.1
13	167.0	75.0	28.45	196.1	847.8	1,972.0	0.80	5,340.0	2,422.2
14	167.0	75.0	28.45	196.1	108.9	253.3	0.15	26,214.9	11,890.9
15	140.0	60.0	14.22	98.1	108.9	253.3	0.15	26,214.9	11,890.9
16	122.0	50.0	28.45	196.1	388.6	903.9	0.50	12,015.2	5,450.0
17	129.2	54.0	28.45	196.1	204.3	475.2	0.36	33,041.8	14,987.5
18	95.0	35.0	28.45	196.1	16.6	38.6	0.36	33,041.8	14,987.5
19	95.0	35.0	64.00	441.3	16.6	38.6	0.36	33,041.8	14,987.5
20	95.0	35.0	64.00	441.3	16.6	38.6	0.36	24,003.7	10,887.9
21	95.0	35.0	64.00	441.3	16.6	38.6	0.36	9,038.1	4,099/6
22	136.4	58.0	64.00	441.3	211.0	490.8	0.50	12,015.2	5,450.0
23	95.0	35.0	64.00	441.3	34.2	79.6	0.50	12,015.2	5,450.0
24	167.0	75.0	64.00	441.3	186.1	432.9	0.36	24,003.7	10,887.9
25	167.0	75.0	64.00	441.3	801.0	1,863.1	0.92	2,977.1	1,350.4

Table 3 - Continued

Point No.	Temperature		Pressure		Enthalpy		Concentration	Weight	
	^oF	^oC	psia	kPa	BTU/lb	KJ/kg	lb/lb or kg/kg	lb/hr	kg/hr
26	167.0	75.0	64.00	441.3	99.0	127.9	0.28	21,026.6	9,537.5
27	132.8	56.0	28.45	196.1	99.0	127.9	0.28	21,026.6	9,537.5
28	175.0	79.4	-	-	-	-	water	559,924.0	253,977.3
29	163.0	72.8	-	-	-	-	water	559,924.0	253,977.3
30	85.0	29.4	-	-	-	-	water	381,156.0	172,889.5
31	105.0	40.5	-	-	-	-	water	381,156.0	172,889.5
32	85.0	29.4	-	-	-	-	water	399,908.0	181,395.9
33	105.0	40.5	-	-	-	-	water	399,908.0	181,395.9
34	85.0	29.4	-	-	-	-	water	106,775.6	48,433.5
35	105.0	40.5	-	-	-	-	water	106,775.6	48,433.5

Table 4

Technical and economical comparison of Rankine Cycle and Texergy Cycle systems for waste-heat recovery from Transamerica DeLaval Diesel engine DSRV-12-4 (- 5.217 KW).

		Rankine Cycle System	Texergy Cycle System I	Texergy Cycle System II
1.	Gross (turbine) output KW	613.4	741.3	875.4
2.	Auxiliary (pumps) power KW	36.0	11.0	14.5
3.	Net power output KW	577.4	730.3	860.9
4.	Turbine efficiency %	71.0	71.0	75.0
5.	Thermal efficiency %	15.7	20.5	15.2
6.	Exergy (Second-Law) efficiency %	40.4	51.8	51.9
7.	Exergy utilization efficiency %	32.3	51.0	48.2
8.	Internal cycle efficiency %	57.1	72.9	69.2
9.	Nameplate recovery ratio %	11.0	13.9	16.5
10.	Specific cost $/KW	2,200.0	1,286.0	1,359.0