Influences of energy economy on steam turbine design

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ABSTRACT: The pulp and paper industry uses condensing, backpressure, and automatic extraction types of steam turbines. Small drive turbines have better efficiency with multiple stages. The author presents a summary of some alternate steam turbine designs and shows the impact on operating energy costs. There is a summary of operating parameters for various cogeneration design options with illustration of the relative energy cost of each of the various designs.

KEYWORDS: Design, economics, efficiency, energy conservation, steam turbines.

The popularity of steam turbines in industrial applications is due to their relative simplicity, reliability, and low maintenance cost. Space requirements for steam turbine drives are commonly lower than for reciprocating engines. In addition, the foundation requirements are less than for reciprocating engines.

Industrial steam turbine cogeneration designs have either "condensing" or "backpressure" modes. In the condensing mode, steam from the turbine exhaust condenses in a heat exchanger similar to the local utility generating plant design. An industrial cogenerator generally uses the backpressure mode for economic reasons unless local utility rates are excessively high or industrial fuel cost is low.

The major economic advantage for industrial cogeneration occurs with the backpressure mode. The main advantage is the ability to extract power from the steam for generation of electricity and to exhaust the steam for process consumption. Power cogeneration becomes a by-product of the prime mover turbine. In the design of modern steam turbine drives and cogeneration plants, it is necessary to evaluate the economics of the comprehensive plant energy cycle to ensure maximum profitability.

The following factors are components of an energy cycle evaluation:

- Fuel costs
- Purchased power costs
- Mechanical drive efficiency
- Condensing cycle efficiency
- Backpressure cycle efficiency
- Process steam requirements.

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Types of steam turbines

The pulp and paper industry uses three major types of steam turbines: condensing, backpressure, and automatic extraction. The automatic extraction units may be either a condensing or a noncondensing design.

Condensing turbines have steam admission at a single pressure level and steam exhaust at one pressure level which is below the atmospheric condition. Noncondensing turbines have steam admission at one pressure level and steam exhaust at a pressure equal to or above the atmospheric condition. Automatic extraction turbines have steam admission at one pressure level and steam exhaust at one or more controlled pressure levels. It is possible to direct the exhaust steam to a condenser.

The pulp and paper industry does not commonly use other steam turbine designs such as induction, multiple inlet, and reheat.

Design considerations for small drive turbines

Small steam drive turbines are generally less than 10,000 hp. Major design considerations for these turbines include inlet steam conditions, exhaust steam conditions, and rotor construction. In their simplest design, small drive turbines have single-stage construction. It is possible to gain significant operating efficiency by using multiple-stage construction, however. **Figure 1** illustrates the impact of turbine multiple stages on operating efficiency.

I. Evaluation of the design alternatives for small steam drive turbines

	Design A 7 multi-stages, back-pressure, low pressure	*Design B 7 multi-stages, back-pressure, high pressure*	*Design C 7 multi-stages, back-pressure, higher pressure*	*Design D 5 multi-stages, back-pressure, low pressure*	*Design E 7 multi-stages, conden-sing low pressure*	*Design F 7 multi-stages, conden-sing high pressure*	*Design G 7 multi-stages, conden-sing higher pressure*
Output, bhp	1,800	1,800	1,800	1,800	1,800	1,800	1,800
Generator efficiency, %	94.5	94.5	94.5	94.5	94.5	94.5	94.5
Equivalent output, kW	1,268	1,268	1,268	1,268	1,268	1,268	1,268
Inlet steam conditions:							
Pressure, psig	300	600	1,200	300	300	600	1,200
Temperature, °F	520	590	670	520	520	590	670
Heat value, Btu/lb	1,269	1,282	1,288	1,269	1,269	1,282	1,288
Backpressure exhaust steam conditions:							
Pressure, psig	10	10	10	10	0	0	0
Temperature, °F	240	240	240	240	0	0	0
Heat value, Btu/lb	1,064	1,064	1,064	0	0	0	
Condensing steam conditions:							
Pressure, in. Hg	0	0	0	0	27	27	27
Temperature, °F	0	0	0	0	130	130	130
Heat value, Btu/lb	0	0	0	0	795	795	795
Condenser condensate,Btu/lb	0	0	0	0	98	98	98
Available enthalpy, Btu/lb	205	218	224	205	474	487	493
Theoretical steam rate, lb/hp·h	12.41	11.67	11.36	12.41	5.37	5.22	5.16
Turbine efficiency, %	72	66	63	50	71	68	66
Turbine efficiency, % (corrected)	72	66	63	50	71	68	66
Steam rate, lb/hp·h	12.41	11.67	11.36	12.41	5.37	5.22	5.16
Actual steam rate, lb/hp·h	17.24	17.68	18.03	24.82	7.56	7.68	7.82
Steam rate, lb/kW·h	16.65	15.66	15.24	16.65	7.20	7.01	6.92
Total steam, lb/h	31,024	31,827	32,449	44,675	13,607	13,828	14,073
Economic evaluation:							
Steam cost, US$/MMBtu	3	3	3	3	3	3	3
Operating time, days/year	355	355	355	355	355	355	355
Energy cost, US$/year	162,562	177,340	185,785	234,089	407,259	418,470	428,062

There are a variety of inlet steam conditions for operation of the drive turbine. In some cases, the existing plant steam system configuration may establish the conditions. As a rule, one will use minimum inlet steam and exhaust pressure levels. Application of this rule will ensure minimum energy consumption by the drive turbine.

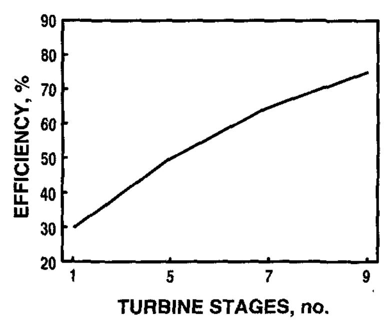
Application

Alternative turbine designs were ev luated for an 1800 hp steam turbine dri en compressor. This size turbine uses m ltistage turbine construction to pro ide maximum operating efficiency. The plant steam system in this example has multiple steam pressure levels of 300 psig, 600 psig, and 1200 psig for driving the turbine. A 10-psig steam header is available for backpressure operation of the drive turbine. There is sufficient condenser capacity for operation of the drive turbine in the condensing mode.

Table I presents a summary of the alternative designs for the steam turbines. **Figure 2** illustrates the impact of the alternative steam turbine configurations on operating energy costs.

Design option A has seven multistages and uses 300 psig steam pressure with 10 psig backpressure. Design options B and C are the same except they use 600 psig and 1200 psig steam pressure respectively. Design option D uses five multistages with 300 psig steam pressure and 10 psig backpressure. Design options E, F, and G are condensing units with 27 in. Hg pressure and 300 psig, 600 psig, and 1200 psig pressure respectively.

1. Effect of turbine stages on efficiency

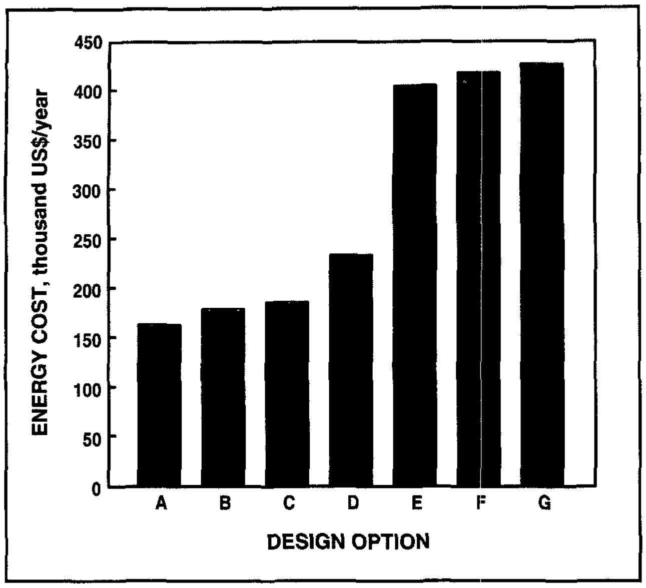


II. Cogeneration turbine design evaluation

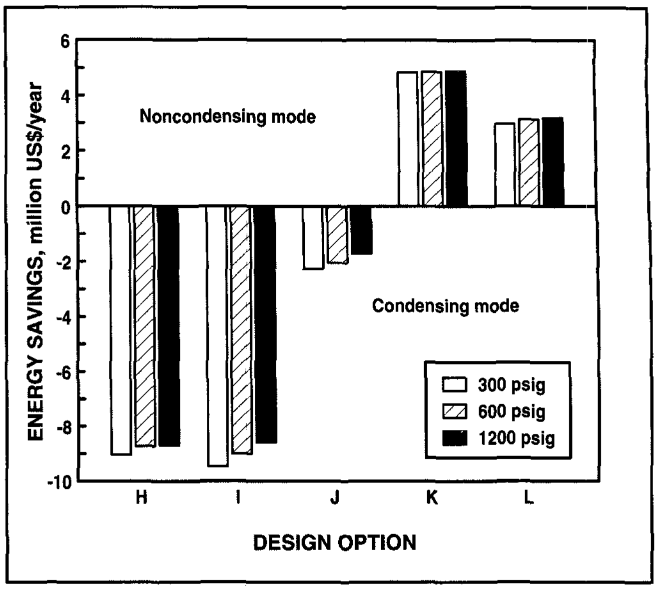
	Design H, condensing mode			Design I, condensing mode			Design J, condensing mode		
Inlet conditions:									
Pressure, psig	300	600	1200	300	600	1200	300	600	1200
Temperature, °F	530	590	670	530	590	670	530	590	670
Enthalpy, Btu/lb	1274	1280	1285	1274	1280	1285	1274	1280	1285
Quantity, lb/h	800,000	800,000	800,000	800,000	800,000	800,000	800,000	800,000	800,000
First extraction:									
Pressure, psig				150	150	150	150	150	150
Temperature, °F				420	420	420	420	420	420
Enthalpy, Btu/lb				1228	1228	1228	1228	1228	1228
Quantity, lb/h				300,000	300,000	300,000	300,000	300,000	300,000
Second extraction:									
Pressure, psig							50	50	50
Temperature, °F							320	320	320
Enthalpy, Btu/lb							1190	1190	1190
Quantity, lb/h							300,000	300,000	300,000
Exhaust:									
Pressure, psig									
Temperature, °F									
Enthalpy, Btu/lb									
Quantity, lb/h									
Condensing:									
Pressure, in·Hg	27	27	27	27	27	27	27	27	27
Temperature, °F	106	106	106	106	106	106	106	106	106
Enthalpy, Btu/lb	1045	1045	1045	1045	1045	1045	1045	1045	1045
Quantity, lb/h	800,000	800,000	800,000	500,000	500,000	500,000	200,000	200,00	200,000
Turbine:									
Power, hp	57,610	59,119	59,623	23,119	25,486	27,053	18,123	19,714	20,932
Efficiency, %	80	80	79	80	80	79	79	78	77
Actual rate, lb/hp·h	13.9	13.5	13.4	34.6	31.4	29.6	44.1	40.6	38.2
Generator:									
Efficiency, %	95	95	95	95	95	95	95	95	95
Electricity, kW	40,812	41,881	42,238	16,378	18,054	19,165	12,838	13,966	14,828

	Design K, noncondensing mode			Design L, noncondensing mode		
Inlet conditions:						
Pressure, psig	300	600	1200	300	600	1200
Temperature, °F	530	590	670	530	590	670
Enthalpy, Btu/lb	1274	1280	1285	1274	1280	1285
Quantity, lb/h	800,000	800,000	800,000	800,000	800,000	800,000
First extraction:						
Pressure, psig				150	150	150
Temperature, °F				420	420	420
Enthalpy, Btu/lb				1228	1228	1228
Quantity, lb/h				300,000	300,000	300,000
Second extraction:						
Pressure, psig				50	50	50
Temperature, °F				320	320	320
Enthalpy, Btu/lb				1190	1190	1190
Quantity, lb/h				300,000	300,000	300,000
Exhaust:						
Pressure, psig	10	10	10	10	10	10
Temperature, °F	270	270	270	270	270	270
Enthalpy, Btu/lb	1175	1175	1175	1175	1175	1175
Quantity, lb/h	800,000	800,000	800,000	200,000	200,000	200,000
Condensing:						
Pressure, in·Hg						
Temperature, °F						
Enthalpy, Btu/lb						
Quantity, lb/h						
Turbine:						
Power, hp	25,217	25,755	26,289	16,615	17,598	18,181
Efficiency, %	81	78	76	80	77	74
Actual rate, lb/hp·h	31.7	31.1	30.4	48.2	45.5	44.0
Generator:						
Efficiency, %	95	95	95	95	95	95
Electricity, kW	17,864	18,245	18,624	11,770	12,467	12,880

2. Operating energy cost for various small drive turbine designs



3. Relative energy savings for cogeneration turbines



Design option A of Fig. 2 using 300 psig inlet steam and 10 psig backpressure offers the most economical drive turbine operation which is consistent with the existing plant steam system configuration and no pressure-reducing station operation.

Design considerations for cogeneration turbines

Steam turbine drives for cogeneration in the pulp and paper industry may range from 10,000 hp to 100,000 hp. The design of these large cogeneration turbines consists of multiple stages, advanced rotor and reaction blade design, and labyrinth shaft seals for optimum operating efficiency.

A combination of a number of factors determines turbine design and operating conditions:

- Process steam requirements
- Process power requirements
- Plant steam system configuration
- Local fuel cost
- Purchased power cost and availability.

Application

A new turbine generator set is necessary for process steam and electrical generation in an existing facility. The existing plant steam system of this example has operating pressure levels of 1200 psig, 600 psig, 300 psig, 150 psig, 50 psig, and 10 psig. Local fuel costs are US$ 3/MMBtu. Utility power cost is U.S.$ 0.045 per kW·h. Consumption is at an average rate of 25,000 kW.

The author evaluated the following turbine operating options: straight condensing, single extraction and condensing, double extraction and condensing, straight backpressure, and double extraction and backpressure. **Table II** is a spreadsheet summary of operating parameters for these turbine design options. **Figure** 3 illustrates the relative energy cost of each cogeneration set design.

Design option K represents the most economical operation. It uses straight backpressure operation at 10 psig. Turbine inlet steam pressure has little net effect on operating energy cost. One can select turbine inlet steam pressure using an optimum integration with the existing steam configuration.

Conclusion

Careful evaluation of the comprehensive mill energy balance is a prerequisite for the most economical selection and design of steam turbines for drive and cogeneration applications.

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