Cogeneration Systems: Balancing the Heat-Power Ratio

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Cogeneration is the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream. Essentially, the same fuel works "twice," achieving high thermal efficiencies. Cogeneration economics are good when the system can fully use available electrical and thermal energies from the system. Resulting high thermal efficiencies translate into lower fuel costs and help achieve higher return on investment.

The design of a cogeneration power plant is based on how the actual thermal and power loads match available thermal and power outputs of the prime movers. If a ready market exists for excess heat or power, then heat-power ratio balancing is not critical.

For example, if power can be exchanged (under desired terms), then the site thermal energy requirement becomes the basis of cogeneration system operation (thermal load following). The excess power can be sold or a power shortage can be met by imported power. Thermal efficiency remains high and the actual power plant heat-power ratio matches site requirements.

For an example of a favorable heat-power ratio, imagine an existing fire-tube boiler that produces 10,000 lbs/h (4540 kg/h) steam at 120 psig (about 8 bars g) and consumes 15 million Btu/h (4400 kWt) of fuel gas input (average 75% boiler efficiency). The same amount of fuel input to a standard 1.2 MW gas turbine could produce the required amount of steam using a waste heat recovery boiler. As a bonus, about 1,100 kWe electric power could be produced "free" of any fuel cost. This is an example of a highly favorable heat-power ratio and because of this the system provides attractive cogeneration economics.

Now imagine an absorption chiller feeding an air-conditioning system with the same steam requirement. During part-load operation, the same gas turbine generates electricity in an inefficient manner (normally). Not much waste heat can be used for this system unless another need exists at the site. The economics of cogeneration would not make sense if part-load operation occurred for long periods.

So, how does a cogeneration system designer handle these extreme heat-power ratios covered, in addition to varying heat-power ratio changes for diurnal and seasonal requirements?

Typical methods for heat-power ratio balancing include:

Method 1: Gas Turbine and Gas Engine Generators

First is a power plant configuration that combines low-efficiency gas turbine generators (producing more waste heat, higher heat-power ratio) with efficient gas engine generators (for low heat-power ratio). The total power capacity requirement could be shared between gas turbine and gas engine generators to allow

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flexibility in choosing the most optimum prime mover for part-load operation.

Cogeneration power plant configurations sometimes require prime movers with very different heat-power ratios due to varying loads as shown below.

Example A. Typically, a centrally air-conditioned building will have high cooling load requirements under peak design conditions, requiring high thermal energy if absorption chillers are operating on cogenerated waste heat. This building requires 500 tons (1760 kW) of cooling and about 1,100 kW of electric power for peak capacity requirements. A gas turbine generator could operate at high cogeneration efficiency as follows:

1. Gas turbine performance at 95°F (35°C), 1,200 kW electric power, 18.2 million Btu/h (5340 kWt) fuel input (22.5 % thermal efficiency), exhaust 15.5 lb/s (7 kg/s) at 1,004°F (540°C).

2. Waste heat recovery boiler performance in Example A's conditions would provide about 10.2 million Btu/h (2990 kWt) for a single-stage absorption chiller. With 7 % thermal energy losses (radiation and hot water pipe losses), the required 250°F (121°C) hot water would be supplied to the absorption chiller(s) for 500 tons cooling capacity.

3. Heat-power ratio (MBtu/h thermal energy per kWh) in Example A is 8.5 (10,200/1,200).

Example B. For the same typical building in Example A, if the requirement is only 750 kW electric power and 175 tons of air conditioning in part-load operation, the heat-power ratio would be different as follows:

1. Gas engine performance at 77°F (25°C), 750 kW electric power, 6.8 million Btu/h (2000 kWt) fuel input (37.5% thermal efficiency), waste heat availability of 1.22 million Btu/h (359 kW) from jacket water, 0.34 million Btu/h (100 kWt) from after-cooler circuit and 1.7 million Btu/h (500 kWt) from engine exhaust.

2. This total 3.3 million Btu/h (959 kWt) waste heat would produce about 175 tons of cooling using a more economical one-stage absorption chiller with 194°F (90°C) hot water.

3. Heat-power ratio (MBtu/h thermal energy per kWh) in Example B is 4.4 (3,300/750).

Heat-power ratio changes from a peak-load condition requiring 8.5 (with gas turbine generator) to reduced part-load operation that needs only 4.4 heat-power ratio, which can be met economically by a gas engine generator. Selecting a combination of prime movers allows for optimum operation of gas turbine-gas engine load sharing for highest cogeneration efficiency during changing heat-power ratio requirements.

Method 2: Hybrid Chillers

Cogeneration power plants that provide waste heat for central air-conditioning systems require a hybrid chiller for heat-power ratio balancing. At times of comparatively lower electric power load (when low waste heat is available for absorption chiller), an electric chiller helps heat-power ratio balancing by

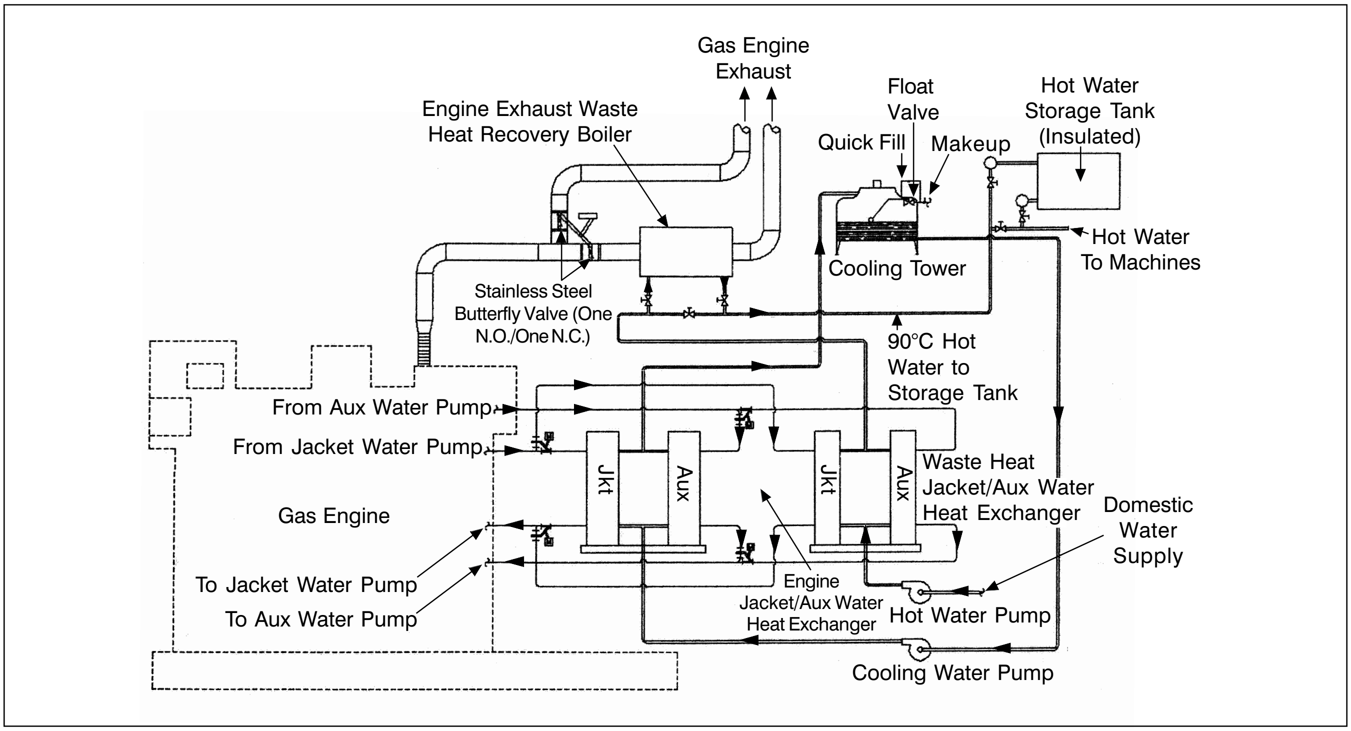

Figure 1: 900 kW gas engine cogeneration power plant for 90°C hot water production.

increasing the electrical load, which increases waste heat for cogeneration efficiency.

Method 3: Thermal Energy Storage

Thermal energy storage is typically used for cooling applications. However, using storage tanks for heating applications with low temperature hot water (85°C to 90°C [185°F to 194°F]) can "save" available waste heat, thus, matching on-site power generation requirements. The system could be designed for a hot water temperature above 100°C (212°F) (pressurized system), if such a thermal demand existed.

Since it is not economical to "store" electric power (especially for small cogeneration power plants), excess thermal energy must be stored to ensure a high thermal cogeneration efficiency to meet electrical power needs.

Using full waste heat in cogeneration application for central air-conditioning requires that heat-operated chillers be operated at maximum capacity and all excess cooling capacity be stored as chilled water in storage tanks. Existing water tanks (especially those for emergency firefighting) or specially built tanks may be used.

Thermal storage can be used for hot water in the range of 85°C to 95°C (185°F to 194°F) (as used extensively in composite textile mills). Since a cogeneration power plant produces hot water continuously, hot water can be stored in tanks to meet manufacturing demands.

Figure 1 shows a simple piping schematic for hot water generation and storage system as part of a cogeneration power plant using 900 kW, 1,000 rpm, turbocharged gas engine-generator. The figure does not show all required control valves and instrumentation for safe and economical operation.

Method 4: Gas Turbine Inlet Conditioning

Example A. Gas turbine inlet conditioning is one technology that can be used with gas-turbine generators for power-heat ratio balancing. It uses inlet air cooling for increase in peak capacity performance in summer (either from thermal storage or on-line chillers using waste heat) or inlet air heating for increase in part-load cogeneration efficiency, specially in winter (availability of increased waste heat energy per kWe generated).

Inlet air cooling increases capacity and efficiency of the gas turbine generator and is used extensively in cogeneration systems with waste heat used for a central chilled water supply, with or without thermal storage. This design allows operation of gas turbine generators as per required loads because the increase in peak electrical power generation due to inlet air cooling also results in an increase in available waste heat for absorption chillers.

Under part-load conditions, a gas turbine with inlet air cooling coils is at a disadvantage since the additional pressure drop in the, now redundant, cooling coil causes an increased heat rate (higher fuel consumption). In a cogeneration installation, part-load efficiencies can be increased as shown in *Table 1* covering a typical nominal 1200 kW rated gas turbine in cogeneration plant producing 3 bar (a) steam for industrial use. At 40% part-load operation, inlet air heating for gas turbine (limited by OEM design) could be used to balance required heat-power ratio since lower gas turbine efficiency results in higher waste heat availability, with overall high cogeneration efficiency. Under the previous conditions, it is noted that cogeneration efficiency increases by more than 15% when inlet air is heated from 60°F (15°C) to 140°F (60°C) under part-load conditions. Most gas turbine manufacturers have readily available performance data up to 140°F (60°C) inlet air temperature. The limit of inlet air heating should be checked with the gas turbine manufacturer before designing this option.

Example B. Supplemental firing is used in waste heat stream, to increase "waste" heat generation in oxygen-rich gas turbine high temp. exhaust. Higher heat availability will mean higher heat-power ratio, which could be used to improve cogeneration economics.

Gas Turbine Performance				
Ambient Temp.	15°C	30°C	45°C	60°C (Extra-Polated)
Load	40%	40%	40%	40%
Output Power	436 kW	385 kW	334 kW	283 kW
Efficiency	16.04%	14.92%	13.51%	11.81%
Exhaust Gas Flow	6.35 kg/s	6.02 kg/s	5.61 kg/s	5.21 kg/s
Exhaust Gas Temp.	336°C	355°C	378°C	405°C
Exhaust Thermal Power	2140 kW	2061 kW	1975 kW	1882 kW
Cogeneration Plant Performance				
Ambient Temp.	15°C	30°C	45°C	60°C
Sat. Steam Pressure	3 Bars A	3 Bars A	3 Bars A	3 Bars A
Steam Production	4123 kg/h	4321 kg/h	4494 kg/h	4642 kg/h
Cogeneration Plant Efficiency	65.29%	69.1%	72.49%	75.46%

Table 1: 1200 kW cogeneration plant performance part load.

Conclusion

Cogeneration systems operate efficiently if all, or most, of the electric and thermal energies are used. In actual practice, loads do vary and heat-power ratio balancing is required in most system designs to ensure efficient and economical operation of cogeneration power plant.

Systems for heat-power ratio balancing should be built into the basic cogeneration power plant configuration right from the beginning to ensure optimum utilization of available power and heat outputs and thus produce savings in fuel costs, resulting in attractive economic returns.