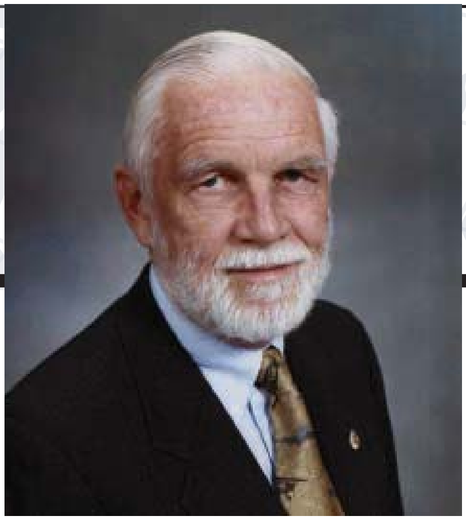
As the Turbine Turns



Gas Turbines - Major Greenhouse Gas Inhibitors

by Lee S. Langston, *Professor Emeritus, Mechanical Engineering, University of Connecticut*

In the last twenty-five years, the development and deployment of combined cycle gas turbine (CCGT) power plants represent a technology breakthrough in efficient energy conversion, and in the reduction of greenhouse gas production. It is one, in my opinion, that has been largely unrecognized by the popular press in their writing about energy and greenhouse gas production.

In *The Nature of Technology* [1], author Brian Arthur points out that the evolution of novel technologies arise by the combination of existing technologies, begetting innovation. The CCGT power plant is a superb example of Arthur's definition, where technologies of steam turbines and gas turbines were joined, to form a combined power plant.

As Dietrich Eckardt relates in his excellent *Gas Turbine Powerhouse* [2], CCGT power plants started to be deployed in about 1990. At that time, gas turbine combustor and hot turbine technology had advanced, so that exhaust gas exit temperatures reached the range of 1000 °F (538 °C) in electric power gas turbines. These Brayton cycle exhaust gases were high enough in temperature to pass through a heat recovery steam generator (HRSG) to supply a Rankine cycle steam turbine, generating more electrical power.

Thus the resulting combined power plant (Brayton and Rankine) generates electrical power from two prime movers, using one unit of fuel. The fuel of choice is predominantly clean-burning natural gas, with fuel oil frequently used as a backup. Using conservation of energy and the definition of thermodynamic thermal efficiency η, the combined cycle thermal efficiency, η_{CC}, can be derived fairly simply as,

$$\textbf{(1)} \qquad \eta_{CC} = \eta_B + \eta_R - \eta_B \eta_R$$

where η_B and η_R are thermal efficiencies of the Brayton and Rankine cycles, respectively. Taking η_B = 40% (a good value for modern gas turbines) and η_R = 30% (a reasonable value at typical CCGT conditions), the sum minus the product in Eq. (1) yields η_{CC} = 58%, a value of combined cycle efficiency greater than either of the individual efficiencies.

Currently, in my home state of Connecticut we have CCGT power plants that range from 25 MW (here at the University of Connecticut) to 840 MW in the town of Dayville. On May 19, 2011 Siemens announced it had reached a record thermal efficiency of 60.75% at its new 578 MW CCGT power plant in Irsching, Germany, making it probably the most efficient heat engine ever operated. Since then, Siemens, GE and Mitsubishi have announced CCGT power plants under design and development that will approach an η_{CC} of 65%, more than double the power plant efficiency values I learned about as an undergraduate engineering student.

Natural gas, composed mostly of methane, CH_4, is the hydrocarbon fuel used by CCGT power plants. Methane has the highest heating value per unit mass (24,400 Btu/lbm, (HHV)) of any of the hydrocarbon fuels (e.g. butane, diesel fuel, gasoline, coal, etc.). It is the most environmentally benign of fuels, with impurities such as sulfur (hydrogen sulfide) removed before it enters the pipeline. The chemical reaction for stoichiometric combustion of methane with O_2 in air is

$$\textbf{(2)} \qquad CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \Delta H$$

to produce carbon dioxide and water, where ΔH is the heating value (also called heat of combustion, or heat content). Using stoichiometry, Eq. (2) shows that for 1 lbm of methane, 2.74 lbm of carbon dioxide, a greenhouse gas, is produced.

King Coal and Prince Methane

Roughly 40% of the world's electricity is generated in Rankine cycle coal-fired power plants. According to the Energy Information Administration (EIA) [3], in 2014, U.S. coal-fired plants accounted for 76% of the carbon dioxide emissions for the U.S. electric power sector.

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If a significant portion of these coal-fired Rankine cycle plants were replaced by the latest natural gas-fired CCGT power plants, anthropogenic carbon dioxide released into the earth's atmosphere would be greatly reduced. Two contributing factors bring this about:

1) More efficient plants burn less fossil fuel. As we saw above, the latest CCGT power plants operate at thermal efficiencies of 60% (or higher). Using EIA data[4] for coal-fired steam plants in the U.S., their average thermal efficiency is 30% (it is 33% for natural gas) for plants operating over 7 years in 2007-2013. Thus, the latest CCGT power plants' efficiencies are double that of the average U.S. coal-fired steam plant in operation.

2) The amount of carbon dioxide produced when a fuel is burned is a function of its carbon content and its heat content (heat of combustion). A measure of this is the carbon dioxide emissions coefficient, Υ. Using EIA data[5], the emissions coefficient for natural gas is Υ_{NG} = 117.0 lbm CO_2/MBtu, a ratio of the mass of CO_2 produced to its heat content (HHV). The emissions coefficient for subbituminous coal is Υ_C = 214.3 lbm CO_2/MBtu. (This class of coal is used primarily as fuel for steam-electric power generation.) Thus on an energy input basis, coal can produce more carbon dioxide mass than natural gas by a factor of 1.8.

Efficiencies and Emissions

Just how do these two factors, the difference in plant efficiencies and in CO_2 emissions play out for greenhouse gas production? We can evaluate each, by comparing the rate of anthropogenic production of CO_2, $\dot{n}$, where $\dot{n} = \Upsilon \Delta H \dot{m}$ and $\dot{m}$ is the mass rate of fuel flow.

Figure 1 shows a sketch of two control volumes, one for a coal-fired Rankine cycle power plant (subscript R) and one for a

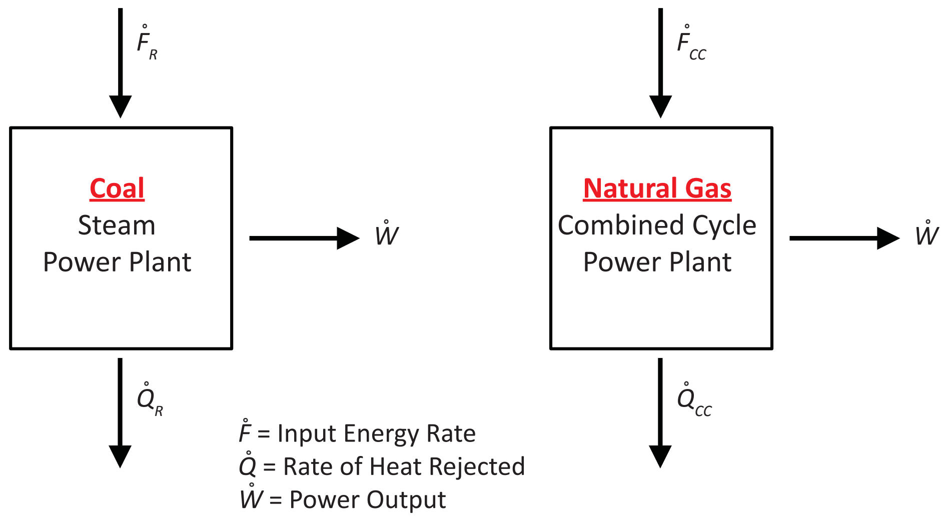

Figure 1 – Control volumes for Rankine Cycle and CCGT power plants, each with equal power output, $\dot{W}$.

natural gas CCGT power plant (subscript CC), each with an identical power output of $\dot{W}$. Using the appropriate values for each power plant, the fuel energy rate input is $\dot{F} = \dot{m}\Delta H$. From Fig. 1, and the symbol definitions given above, the ratio of rate of CO_2 production for the Rankine (R) coal-fired plant and the natural gas combined cycle plant (CC) is then given by

(3) $$\frac{\dot{n}_R}{\dot{n}_{CC}} = \frac{\eta_{CC}}{\eta_R}\,\frac{\Upsilon_c}{\Upsilon_{ng}}$$

Equation (3) clearly shows the effect of both plant efficiency and hydrocarbon fuel carbon content/heat content.

Using efficiency values (30% and 60%) and emission values given above, Eq. (3) yields a CO_2 production rate ratio of 3.63. Thus, replacing a coal Rankine cycle power plant with a natural gas CCGT power plant reduces CO_2 by a factor of almost four, resulting in a substantial 75% reduction in CO_2 production.

Because of recent shale gas developments in the U.S., many coal-fired Rankine cycle plants are switching over to cheaper natural gas. However, Eq. (3) (where ηR = 33% for the use of natural gas) still yields a 45% reduction in CO_2 production by the use of a CCGT.

Sustainable energy advocates may say that these CCGT CO_2 reductions still do not make greenhouse gases go to zero. But when the sun doesn't shine and when the wind doesn't blow (or blows too hard) we all know that we need reliable, on-demand electrical power at a reasonable cost. This can be provided by existing gas turbine CCGT technology, with a minimum of greenhouse gas production.

References

1. Arthur, W. Brian, 2009, ***The Nature of Technology,*** Free Press, p. 21.
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3. "How much of U.S. carbon dioxide emissions are associated with electricity generation?", March 31, 2015, EIA, <www.eia.gov/tools/faqs/faq.cfm?id=77&t=11>.
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