THE KEY ROLE OF HEAT EXCHANGERS IN CLOSED BRAYTON CYCLE GAS TURBINE POWER PLANTS

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ABSTRACT

In the power generation field, simple cycle gas turbines are dominant, with heat exchanged variants only selected based on particular user's requirements. For the lesser known closed Brayton cycle (CBC) power plant, heat exchangers are mandatory. The following three categories of heat exchangers are addressed in this paper, 1) heat input to the closed cycle from an external source; for example the heat exchanger in a fluidized bed combustor in the case of a fossil-fired plant, or an intermediate heat exchanger (IHX) in the case of an indirect cycle nuclear gas turbine, 2) recuperator in the system to enhance efficiency, and 3) exchangers (i.e., precooler and intercooler) for heat rejection from the system. The influence that these heat exchangers have on the selection of system parameters, and plant performance is discussed. Heat exchanger technology state-of-the-art for CBC systems is highlighted.

1. INTRODUCTION

By virtue of its closed loop nature, the CBC plant is heat exchanger intensive, and the power conversion loop includes a heat source exchanger, recuperator, precooler, and intercooler(s). Collectively, these have a strong effect on the plant efficiency, and the selection of optimized system parameters, a prime example being the compressor pressure ratio. The heat exchanger(s) size, geometric proportions, and cost are influenced by the following, 1) performance requirements (i.e., high effectiveness and low pressure loss), 2) thermal and transport properties of the working fluid (e.g., helium, inert gas mixture, air, nitrogen, etc), and 3) integration of the units with the turbomachinery.

The heat source exchanger is the most demanding because of its elevated temperature operation. There are two major heat sources to be considered, 1) fluidized bed combustor for fossil operation, and 2) the use of a high temperature reactor (HTR) in conjunction with an IHX.

For the gas-to-gas recuperator, attractive configurations can be realized by utilizing compact plate-fin surface geometries. For the precooler and intercooler, both of which are gas-to-water heat exchangers, additional fabrication, inspection and repair considerations, favor the use of tubular surface geometries.

Heat exchanger requirements unique to CBC systems are addressed, together with how they are needed from the plant efficiency standpoint. This results from the fact that the turbine inlet temperature is much lower than in open cycle gas turbines because of heat source (fossil and nuclear) temperature limitations. Well established technology bases exist for CBC gas turbine plant heat exchangers. A major point noted is that the heat exchangers cannot be designed in an isolated manner, but must be addressed on an integrated basis as part of the overall CBC power conversion system design.

2. CBC - A FUEL NEUTRAL GAS TURBINE

The CBC has two major attributes, 1) with an external heater a wide variety of fuels can be used, and 2) the reject heat is sensible (as opposed to latent in the case of the Rankine cycle), and with a high heat content (dissipated over a wide temperature range) has economic worth (e.g., cogeneration). For the most simple CBC variant (i.e., non-intercooled cycle) its adaptability to a wide range of heat source and waste heat rejection alternatives is shown on Figure 1. Since the fuel neutral nature of the CBC has been mentioned previously (McDonald and Etzel, 1995), only the major heat source candidates will be discussed here.

2.1 Fossil-Fired Plants

Between 1955 and 1975 about 20 closed cycle gas turbine plants operated, mainly in Germany (Bammert, 1976). With an external heater these plants were fired with dirty fuels, including coal, heavy crude oil, and petroleum coke. Most of the units utilized a pulverized coal heat source. The last fossil-fired CBC plant to see service in Germany was the 50 MW(e) Oberhausen II helium gas turbine which had an external...
heat exchanger fired with coke-oven gas, and this will be mentioned in a later section. These plants, essentially based on 1950's technology demonstrated high degrees of reliability and availability and accumulated an operating time of over one million hours (Keller, 1978).

The major attributes of the early CBC plants included their ability to operate in a combined power and heat production mode (i.e., cogeneration) and utilizing dirty fuels. They were not replicated in large numbers, the reason being essentially twofold, 1) significant advancements in open cycle gas turbine technology, and 2) the availability of cheap clean fossil fuels (e.g., natural gas). As will be outlined in a following section, advancements in heat exchanger technology may result in a renewed interest in the coal-fired CBC plant.

2.2 Nuclear Heat Source

The coupling of a gas cooled reactor with a CBC has been recognized for half a century (McDonald, 1955a). To date the only operation of a closed-cycle gas turbine with a nuclear reactor was undertaken to meet the needs of the U.S. Army. In the late 1950's a research and development program led to the operation of the ML-1 330 KWe trailer mounted system (Varga, 1961). With changes in the Army needs, the project was discontinued in 1965.

Studies of large nuclear gas turbine plant concepts were undertaken in the late 1970's in the U.S. (McDonald and Peinado, 1982) and Germany, but discontinued because of lack of technology readiness. For a smaller plant concept, studies were initiated in the U.S. in 1993 based on a modular reactor and a direct plant cycle conceptual design was established (Neylan, 1995). With the cessation of U.S. Government funding, this program was terminated in the summer of 1995.

With the abandonment of the gas cooled reactor in the U.K., France, Germany and now in the U.S., the lead for research and development of this type of nuclear power plant is in Asia, where small plants are under construction in Japan and China. If the nuclear closed Brayton cycle (NCBC) plant is to become a reality, it will be dependent on the availability of an advanced nuclear heat source being developed for high temperature nuclear process heat (McDonald, 1996a). The Japanese HTTR program is focused on process heat applications. The utilization of such an NHS would entail deployment of an indirect cycle approach (McDonald, 1996b) in which heat exchangers play a major role as will be outlined in a following section.

2.3 Small CBC Systems

Over the last 30 years extensive design and development has been undertaken in the U.S. by AlliedSignal on small closed cycle gas turbines (1-100 KWe). Applications for these units include space power, underwater systems, marine, and for terrestrial power generation (Pietsch, 1985). Various systems have been investigated and demonstrated including fossil, isotope, and solar heat sources. Today work primarily focussed on solar dynamic CBC power generation systems for space station application.

This class of CBC has been included in this paper because the heat exchangers have a major impact on the selection of system parameters and features. For example, in a solar space power CBC the heat exchangers would include the solar receiver, recuperator, and radiator for dissipating the reject heat to space. The major design criteria is minimum weight for the overall system (e.g., heat source, power conversion system, and heat sink). Considering the somewhat conflicting requirements of the rotating machinery and the heat exchangers (in terms of size and weight), an attractive solution involves the use of a helium/xenon gas mixture as the closed-cycle working fluid.

3. THERMODYNAMIC CYCLE/PERFORMANCE

3.1 Role of Heat Exchangers

The well known relationship between temperature and entropy in a power system (Figure 2) is a convenient way of highlighting the four major functions of the exchangers. The most demanding requirement is for the heat source exchanger since it operates at very high temperature and heats the working fluid (from 5 to 6) to turbine inlet conditions. After expansion in the turbine, the gas enters the low pressure side of the recuperator. Internal energy transfer within the cycle takes place in the recuperator, its major role being to minimize the thermal energy input to the cycle. The low pressure gas gives up its heat (7 to 8) to the high pressure compressor discharge gas (4 to 5). It is of interest to note that the recuperator heat duty is greater than provided by the heat source exchanger.

Reject heat from the cycle is removed in the gas-to-water precooler (8 to 1) prior to it entering the low pressure compressor. For simplicity only, a single stage of intercooling is shown on Figure 2. After leaving the LP compressor stages, the compression work is removed in the intercooler (2 to 3). This operation minimizes the power required in the HP compressor (which is proportional to the gas inlet absolute temperature) and this contributes about three percentage points to the cycle efficiency. Following compression in the HP unit, the gas enters the high pressure side of the recuperator. As outlined below the heat exchangers also have other features that impact the plant performance.

3.2 Intercooling

Intercooling is well understood (McDonald, 1994a), and while used extensively in multi-stage gas compressors in process industries, it has not found acceptance in modern gas turbines mainly because it distracts from a beauty of the simple cycle, namely that it does not need a coolant (e.g., water) supply.

For a representative CBC the impact of
intercooling is shown on Figure 3. A number of intercoolers can be considered, but this makes the turbomachinery complex (e.g., increased bearing span). There appears to be little benefit in going beyond two stages of intercooling, since the increased pressure losses in the heat exchangers and in the gas inlet and outlet ducts become significant. For an indirect NCBC plant concept with a high degree of recuperation and two stages of intercooling, an efficiency of about 47% is realizable at a pressure ratio of about three.

3.3 Recuperation

The benefits of using a recuperator in terms of improving gas turbine efficiency are well understood (McDonald, 1990a), but with their high capital cost they have not found wide acceptance for industrial gas turbines. With the current abundance and low cost of natural gas, acceptable power generation economics can be realized with simple open cycle gas turbines.

In the case of the CBC plant the recuperator, in addition to enhancing efficiency, plays an important role in terms of the turbomachinery design. The relationship between compressor pressure ratio and recuperator effectiveness on plant efficiency is shown on Figure 4. For the CBC it is fortunate that high efficiency can be realized at low values of compressor ratio (say around a value of three), since this facilitates a manageable number of compressor stages (less than 20 in each of the LP and HP sections) for the low molecular weight helium working fluid. The plant efficiency is clearly sensitive to recuperator effectiveness, with 95% being realizable with a compact plate-fin heat exchanger.

At pressure ratio values above about three, the decreasing temperature difference between the compressor and turbine discharge gradually negates the use of a recuperator. It is also of interest to note from Figure 4 that the relative exhaust volume flow is near a minimum at a compressor pressure ratio of three. This is important since the volumetric flow at the turbine exit influences the overall diameter of the machine. Also, the centrifugal blade stress in the turbine rear stage is proportional to the product of annulus area and the square of the blade speed. It is clear from this that the recuperator plays a bigger role than just contributing to plant efficiency.

4. HEAT SOURCE EXCHANGERS

4.1 Early Fossil-Fired CBC Plants

In the coal-fired CBC plants a considerable effort was expended on the external heater since it represented about 40% of the overall plant cost. The pulverized coal-fired heaters were operated at atmospheric pressure with most of the heat transfer to the working fluid being by radiation. The maximum turbine inlet temperature for a coal-fired plant was 710°C (1310°F) with a corresponding tube-wall temperature of 760°C (1400°F). Many of the coal-fired plants operated trouble-free for over 100,000 hours, and details of the heaters have been discussed previously (Haas 1966, Harmon 1978).

The last fossil-fired CBC plant to operate in Germany was the 50 MWe Oberhausen II Helium Turbine Plant (Zenker, 1988). The fuel used in this plant was coke-oven gas, and the external heater is worth mentioning because of its advanced design (Innocente, 1977). To reduce the size of the heater the combustion and heat transfer processes were separated. With a hot gas generator the heat transfer was almost exclusively by convection, and a view of the compact heater is shown on Figure 5. This compact heater performed well for the life of the plant which was shutdown in 1988 when the supply of coke-oven gas from a nearby steel plant was discontinued.

4.2 Future Fossil-Fired CBC Plants

The aforementioned heater types have essentially been made obsolete by ever demanding emissions requirements. Both open cycle and closed cycle gas turbines can use circulating fluidized bed combustors to burn low grade fuels which could include coal, biomass, peat, sewage sludge, animal residues, urban and industrial waste, and oil shale. To ensure capture of sulfur and other elements in the bed, and meet environmental regulations, the upper operating temperature is about 900°C (1652°F). At this level of temperature, only a very modest level of plant efficiency can be realized with an open cycle gas turbine. Performance enhancement with a topping heater is possible, but this would require a supply of clean fuel (e.g., natural gas).

The CBC, with its highly recuperated and intercooled cycle, has the potential for efficiency levels above 44% when burning low-grade fuels. More than 15 years ago a development effort was undertaken on a coal-fired fluidized bed combustor for an industrial closed-cycle gas turbine (Campbell 1981, Wright 1982). The Rocketdyne Division of Rockwell International designed, constructed, and successfully operated a coal-fired heater with a working fluid outlet temperature of 855°C (1567°F). With changes in the energy market place, particularly the availability of low cost natural gas this concept did not reach the commercialization stage.

In the mid 1980's a development effort was undertaken by Garrett Corporation (now AlliedSignal) to demonstrate a CBC coupled with a fluidized bed combustor. Burning petroleum coke in the atmospheric fluidized bed the turbine inlet temperature was 788°C (1450°F). The gas turbine rated at 5 MWe operated well for over 8000 hours, and had low emissions, but was not commercialized, largely because of a company realignment (Mason, 1984).

4.3 Nuclear Heat Source Exchanger

Heat exchangers play a key role in gas cooled reactor plants (McDonald, 1994b) and this is particularly true for the indirect cycle (IDC) gas turbine as illustrated on the flow schematic diagram shown on Figure 6. The IHX facilitates transfer of the reactor thermal energy to
the end user, which could be either a hydrogen production facility or an indirect cycle helium gas turbine for power generation. The IHX must be engineered to preclude leakage of radioactivity into the secondary helium loop.

In helium cooled reactors there will always be gas-borne fission products, some small quantity of circulating graphite dust, and tritium (which is known to diffuse through metal at elevated temperature in the primary circuit). The major requirements of the IHX are 1) assured leaktightness (so that the power conversion system will never be exposed to fission products), 2) on-line leakage monitoring, and 3) compact heat exchanger assembly for integration in the steel vessel. These major requirements cannot be met with the existing type of single barrier tubular IHX units.

To meet the above requirements a compact plate-fin IHX concept has recently been proposed (McDonald, 1995b). The overall assembly consists of a number of counterflow modules installed in the steel vessel as shown on Figure 7. The type of construction proposed is similar to units used in the aerospace industry (e.g., air-to-fuel heaters) where hazardous conditions could exist if the two fluids mixed as a result of a leakage in the heat exchanger. A cross section through the proposed counterflow plate-fin IHX is shown on Figure 8. With this type of construction there are two potential leakage paths, 1) leakage under the sealing bars, and 2) failure of the separating tube plate. Compact offset fin surfaces would be used in both the lower pressure (radioactive primary helium) and higher pressure (clean secondary helium) passages. A buffer zone between these two passages would contain a dense finned surface, the pressure in this passage being lower than the primary and secondary helium systems. The value of surface compactness would likely be limited by axial conduction effects, which are well understood for plate-fin counterflow heat exchangers (McDonald, 1975). The brazed unit has a double seal bar at the periphery of the exchanger. The buffer zone passage together with the double headered channel, forms a circuit to facilitate the continuous flow of a small quantity of clean helium purge gas through the interspace.

The double header, gas buffered type of construction has two major attributes, 1) precludes fission products and tritium from ever entering the secondary helium power conversion loop under all modes of plant operations, and 2) facilitates on-line monitoring of the IHX integrity in terms of leak detection (into the buffered gas channels) and identification of the faulty module.

Plate-fin heat exchanger technology is well established and the IHX would take advantage of experience gained with aerospace and gas turbine applications. The proposed IHX is essentially viewed as an extension of existing plate-fin heat exchanger technology used in aircraft fuel heaters.

5. RECUPERATOR

5.1 Early Tubular Units

The recuperators in all of the operated fossil-fired CBC plants were of tubular construction, their technology essentially being an extension of well established boiler technology. This philosophy extended to the design of recuperators for NCBC plants into the 1980's. Using prevailing technology, studies of both the recuperator (McDonald 1977, Van Hagan 1979, Naegelin 1978) and IHX (McDonald, 1980) led to axial flow, counterflow tubular designs, that while felt to be compact in the 1970's, are now viewed as being obsolete.

The aforementioned tubular recuperators were characterized by having modest values of thermal density, usually less than 5 MW/m². This impacted thermal performance since, with limited space available for the recuperator, the effectiveness was less than 90%, simply because of inadequate space to accommodate more heat transfer surface area.

5.2 Plate-Fin Recuperators

Significant advancements have been made in gas turbine recuperator technology since the 1970's (McDonald, 1990b). The compact recuperator (Kretzinger, 1985) permitted utilization of high effectiveness (i.e., 95%) with attendant gains in plant efficiency.

Operating in the clean helium secondary loop, very small hydraulic diameter passages can be used with resultant surface compactness values on the order of three times that in open cycle gas turbine recuperators (McDonald, 1995c). Operating in the laminar flow regime, but with highly offset surfaces, very high heat transfer coefficients can be realized by virtue of the surface geometry, high system pressure, and the high thermal conductivity of helium and this results in a very high thermal density (i.e., 17 MW/m²).

The helium-to-helium recuperator for the IDC gas turbine will benefit from two air-breathing applications, 1) heavy duty industrial gas turbine recuperators in terms of materials, fabrication and high temperature service, and 2) aircraft/aerospace heat exchangers in terms of very compact high performance surface geometries. A representative type of construction for the plate-fin unit is shown on Figure 9.

A comparison (in terms of recuperator surface compactness and thermal density) between air and helium units is shown on Figure 10. Compared with the aforementioned tubular units, the unit size has been reduced by a factor of about four by virtue of the compact plate-fin technology. Existing recuperator technology established by AlliedSignal is directly applicable to the NCBC plant. Over 60 recuperated industrial gas turbines have accumulated over 3 million hours of service. The operating environment for these units, in terms of transients and thermal shock is more severe than those expected in a base-loaded NCBC plant.
In the indirect cycle gas turbine, their are two positive aspects regarding the recuperator; 1) the helium in the power conversion system is non-radioactive, so that the unit will not become contaminated, and 2) the heat exchanger modules are readily accessible for routine inspection, removal/replacement, and hands-on repair as necessary.

6. HEAT SINK EXCHANGERS

The precooler and intercooler are helium-to-water heat exchangers that remove reject heat from the power conversion system. They operate in a very benign environment with metal temperatures less than 121°C (250°F). Extensive work done on steam generators for gas-cooled reactors is germane and represents a good data base in terms of selection of the major features (McDonald 1986, Basol 1990).

A helical bundle geometry is regarded as an attractive solution based on the following, 1) significantly different fluid properties and heat transfer coefficients on the helium and water sides, 2) tubside inspection capability, 3) practical fabrication, 4) structural consideration (pressure, static, seismic, thermal loading), 5) in-situ repair capability, and 6) bundle geometrical proportions for integration in the steel vessel. An attractive design approach would be a counterflow unit with helium flowing outside the tubes, and water inside the tubes. For the intercooler and precooler a thermal density of about 5 MW/m² is viewed as being acceptable.

For the IDC gas turbine, as in the case of the recuperator, the intercooler and precooler are non-radioactive and readily accessible for inspection, maintenance, and removal/replacement as necessary. A significant technology base exists for helical bundle heat exchangers (McDonald, 1994b) and a representative example is shown on Figure 11. The technology for the intercooler and precooler is essentially commercially available.

7. CLOSING REMARKS

Currently, with an abundant supply of low cost natural gas, and many prime-mover types vying for a place in the power generation market, it is unrealistic to project near-term utilization of CBC plants. However, it does have a proven operating record in Europe, and with high efficiency capability it does have long-term potential with both fossil-fired and nuclear heat sources.

There may be a market for small CBC plants burning low grade dirty fuels, and unlike open-cycle gas turbine variants that need a topping heater (burning a clean fuel), the CBC has the potential for high efficiency at modest turbine inlet temperature level dictated by the fluidized bed combustor. The heat exchangers in the CBS (i.e., intercooler, recuperator, precooler) are a major factor in the realization of high efficiency. For a CBC plant fired with a low grade fuel (e.g., coal, peat, biomass, refuse, etc) the power conversion system is regarded as state-of-the-art. Technology transfer from on-going circulating fluidized bed combustor programs would form the basis for the design of the CBC heat source exchanger.

In the case of the NCBC plant, the IDC variant is the most practical concept. This is attributable to the utilization of an IHX since this facilitates the following, 1) operation of the power conversion system in a non-radioactive environment, and 2) the use of conventional gas turbine components. The major challenge is the IHX and an advanced plate-fin concept has been discussed that has the following attributes, 1) assured leak tightness to preclude fission products and tritium from ever entering the secondary power conversion loop, 2) facilitates on-line monitoring of the IHX integrity in terms of leak detection (into the buffered gas channels), and 3) represents a compact heat exchanger assembly for integration in a steel vessel.

A program dedicated to the development of an IHX for a NCBC plant is not foreseen. If this plant is to become a reality it will be because it was a beneficiary of work done in Japan to establish a viable nuclear heat source for high temperature nuclear process heat applications (e.g., hydrogen production).

Plate-fin recuperator technology is well established and data from the aerospace and gas turbine industries are directly applicable. A minimal development effort would be needed to establish a recuperator with high performance (i.e., 95% effectiveness), low pressure loss (i.e., 2%), and compact size (i.e., 17 MW/m²) for integration in a steel vessel.

The precooler and intercooler operate in a very benign environment, and with the use of commercially available technology only a minimum design verification program would be necessary. This paper has put into perspective the role of the three major classifications of heat exchangers in the CBC, namely 1) heat source exchanger, 2) recuperator within the thermodynamic cycle, and 3) the heat sink units (i.e., intercooler and precooler). No technology breakthroughs are necessary in the heat exchanger field, but rather a matter of resolve is needed to facilitate introduction of the CBC plant into the power generation marketplace early in the 21st century.

8. REFERENCES


Fig. 1 CBC Gas Turbine Heat Source and Heat Rejection Alternatives

Fig. 2 Role of Heat Exchangers in CBC Plant

Fig. 3 Effect of Intercooling on CBC Performance

Fig. 4 Effects of Major Parameters on CBC Plant Efficiency
Fig. 5 Tubular Heater for Oberhausen CBC Plant
( Courtesy Sulzer)

Fig. 6 Flow Schematic for NCBC Plant

Fig. 7 Heat Source Concept for NCBC Plant
Fig. 8 Advanced Plate-Fin IHX Concept for NCBC Plant

Fig. 9 Plate-Fin Heat Exchanger Construction (Courtesy AlliedSignal)

Fig. 10 Specific Size Data for Plate-Fin Heat Exchangers

Fig. 11 Representative Helical Bundle Tubular Heat Exchanger (Courtesy General Atomics)