The Increasing Role of Heat Exchangers in Gas Turbine Plants

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ABSTRACT

In the introductory phase of gas turbine deployment for industrial service there was a natural reluctance to incorporate heat exchangers, although some variants included recuperators and intercoolers to enhance performance, since only modest values of compressor and turbine efficiency could be realized. Today, following half a century of intensive development, the situation is quite different, since high turbomachinery efficiencies contribute to attractive levels of performance for contemporary simple cycle plants. Because further aerodynamic advancements are likely to be incremental in nature, significant increase in plant performance can only be realized by either going to higher turbine inlet temperature, or utilizing more complex thermodynamic cycles, or both. It is in the latter two cases that heat exchangers will play an increasing role in the evolutionary advancement of gas turbine plant efficiency. This paper highlights the potential use of heat exchangers for a wide range of gas turbine applications, including industrial prime-movers, electrical power generation, marine service, and perhaps their ultimate use in aircraft propulsion systems. In the last decade, significant heat exchanger technology advancements have been made, to the point where previous impediments (to their widespread acceptance) associated with reliability, have been overcome. It is encouraging that today many proven heat exchanger hardware options are available to gas turbine users, and this will enhance their utilization across the full spectrum of applications, and indeed in the long-term may well make the simple cycle gas turbine obsolete.

1. INTRODUCTION

After five decades of development, future major component (e.g., compressor and turbine) efficiency advancements are likely to be incremental, and while they will surely continue to advance as a result of a better understanding of flow in turbomachines, significant improvements in plant efficiency will only be realized by utilizing more complex thermodynamic cycles with higher firing temperatures. Within the gas turbine circuit, the two major heat exchangers of interest are the intercooler and recuperator. Both of these units contribute to improved thermal efficiency by reducing the compressor power in the case of the former, and in the latter by a reduction in the combustor temperature rise, the operational economics being improved by reduced fuel requirements. Incorporating an intercooler in a recuperative cycle permits optimum operation at a much higher pressure ratio, with obvious advantages in terms of higher specific power.

The use of a steam generator to capture the otherwise wasted heat from the turbine exhaust, facilitates an increased plant power output by use of either a conventional steam bottoming cycle (many of which are in operation) or power enhancement by steam injection, in which the mass flow and specific heat of the gas flowing through the turbine are boosted without the parasitic compressor power drain. Steam injected industrial gas turbines are currently in vogue and thermal efficiency improvements of up to seven percentage points have been demonstrated (Kolp and Moeller, 1988).

This paper highlights the utilization of various heat exchanger types for a variety of cycles that cover the full spectrum of gas turbine applications from established industrial prime-movers to possible future propulsion and space power systems. In the last decade, significant advancements in heat exchanger technology, particularly for high-temperature service, makes possible the practical near-term utilization of advanced thermodynamic cycles. This technology will assure high operating reliability and retention of the compact and lightweight characteristics of the gas turbine, the two factors, which in the past have been impediments to the general acceptable of heat exchanged engines. There may still be user resistance to these more complex configurations, but the fact remains that to realize gas turbine plant efficiency values in excess of about thirty-five percent, some form of heat exchanger is necessary, and the various options available, which are very user-dependent, is the major theme of this paper. It is further recognized that with the current low cost of clean fossil fuels there is limited interest in resource conservation, and it is perhaps sufficient to say that the technology exists for future very high efficiency gas-turbine prime-movers when fuel availability and economics and environmental concerns become paramount.
2. BACKGROUND

With heat sources as varied as oil, gas, coal and nuclear energy, the steam turbine has represented the mainstay of electrical power generation in the United States for almost 100 years. As this century closes, however, further Rankine cycle advancements will be limited, and this includes higher temperature operation, more complex cycles, and the use of exotic working fluids. As shown in Fig. 1, the thermal efficiency of gas turbines has increased steadily over the last half century, paced essentially by aerodynamic and materials technology advancements. Unlike the Rankine cycle that has reached its zenith, the Brayton cycle has the potential for efficiency values of over 50%.

With many advancements in progress, the path is being paved for the gas turbine to become the dominant prime mover early in the next century (Makansi, 1988). As will be outlined in following sections, it is projected that heat exchangers, in a variety of forms, will play an increasing role to exploit the ultimate efficiency potential of the gas turbine for a wide range of applications.

3. ROLE OF HEAT EXCHANGERS

As will be outlined in the following applications-related section, there are several heat exchangers that can be utilized in gas turbine cycles and their incorporation is very user dependent. A composite industrial gas turbine cycle diagram is shown in Fig. 2. Clearly, as portrayed, it does not represent a practical cycle, but is rather included to illustrate the various heat exchanger options.

Addressing first of all, the heat exchangers that contribute to increasing the power plant efficiency, it is convenient to refer to the simplistic performance trends given in Fig. 1. The thermal efficiency curves are not for definitive engines, but rather reflect modern gas turbine technology with a gas turbine inlet temperature of 1200°C (2192°F). It is sufficient to say that the characteristics are valid enough to illustrate the embodiment of the major heat exchanger types addressed in this paper. The three major ways to improve plant efficiency by utilizing heat exchangers are discussed below.

Reducing the power in the compression process means that more of the turbine gross power is available at the generator. Since compressor power is directly proportional to the inlet absolute temperature, there are two ways whereby the efficiency can be improved. The simplest method is to utilize an air precooler or inlet evaporative cooler. The effectiveness of this is very much dependent on the heat sink available and, clearly, if a cryogenic source was available, it would have a significant impact. A more usual method is to separate the compression process and provide cooling between the stages. A number of intercoolers could be considered, but this makes the turbomachinery more complex, and pressure losses increase in the air inlet and outlet scrolls and ducts. The reason that intercoolers have not found wide acceptance is that they detract from the beauty of the simple cycle gas turbine, namely, that it does not need a coolant supply. Intercoolers can use air cooling, or be of the evaporative type, but a very effective means is to use water
cooling. For plants operating with a steam generator, thermal performance can be optimized by using the intercooler as a feedwater heater.

One impediment (and there are many as will be discussed in a later section) towards the adoption of recuperative engines is the low specific power [kW(e)/kg/s] realizable with the aforementioned modest values of pressure ratio. As can be seen from Fig. 3, simple cycle engines can benefit from pressure ratios approaching 20 to 1. As mentioned above, compressor intercooling increases the temperature differential between the exhaust gas and the combustor inlet air. As can be seen from Fig. 3, moderate to high pressure ratios (with attractive specific power) can be used to advantage (yielding thermal efficiency values of over 40%) in recuperative engines that are intercooled. It is this type of engine that is currently of considerable interest for marine propulsion and power generation.

The third method of improving efficiency is to utilize the high-turbine exhaust temperature for steam generation. Utilizing either the turbine discharge gas, or provisioning supplementary firing, high-quality steam can be generated. To date, the most common use of the steam has been for combined cycle operation, where overall plant efficiencies in the high forties are realizable. Initially, steam injection into the gas turbine combustion chamber proved to be effective to suppress the formation of nitrous oxides. More recently, steam-injected cycles offer an alternative to combined cycles. High efficiencies have been demonstrated by this means, in which the mass flow and specific heat of the gas flowing through the turbine are boosted without the parasitic compressor power drain. An important consideration in the selection of cycle is the availability of a water supply. It is projected that the steam generator will become a key component in future industrial gas turbines.

Additional heat exchangers shown in Fig. 2 are essentially conventional in nature, and include the following. As turbine inlet temperatures continue to rise, there is an ever increasing demand for bleed air for blade, disc, and structure cooling. For high-pressure ratio engines it becomes necessary to incorporate a bleed air cooler to provide an effective supply to the turbine hot section. The fuel heater option is very user-dependent, although it may contribute to an incremental rise in thermal efficiency. Commercially available lube oil coolers are used for the bearing system. The aftercooler is essentially an exchanger incorporated to establish optimum air/gas temperature differentials when operating with a recuperator and steam generator. The multiple role that heat exchangers can play in gas turbine plants is shown as an array in Fig. 4. Clearly, the extent to which the various heat exchangers are deployed (and the appropriate selection of surface geometry), is strongly related to the application, and this is addressed below.

4. HEAT-EXCHANGED GAS TURBINE APPLICATIONS

Since the main theme of this paper relates to engine performance advancement from heat exchanger utilization, a convenient way of portraying thermal efficiency as a function of plant size and type is given in Fig. 5. The bulk of the three recent publications (Gas Turbine World, 1986 and Turbomachinery International, 1988). Miscellaneous data points are included to reflect heat exchanged engines of historical significance. Similarly, efficiency data are included for engine types that will be competing with gas turbines in the market place. Various applications for heat-exchanged gas turbines are highlighted as follows.

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**Fig. 3 Effect of Thermodynamic Cycle Selection on Efficiency of Modern Gas Turbine Plants**

The second way to improve efficiency is simply to reduce the fuel flow by transferring back into the cycle some of the energy otherwise lost in the turbine discharge. The heat exchanger to achieve this is defined as a recuperator (fixed boundary device) in this paper, the term regenerator being applied to a rotary exchanger. The recuperator allows heat from the high-temperature turbine exhaust to be transferred to the compressor discharge air prior to entering the combustor. Thus, a smaller fuel fraction is required to heat the incoming air to the final combustion temperature.

As shown in Fig. 3, the efficiency of recuperative engines is a strong function of the compressor pressure ratio. As the pressure ratio is increased, a point is reached when the temperature of the compressor discharge air exceeds the turbine exit gas, and this obviates the use of a recuperator. While dependent on the turbine inlet temperature and the rotating machinery aerodynamic efficiency, recuperative engines have an optimal thermal efficiency for modest values of pressure ratio (say up 10:1). Many recuperative engines are operating today with higher pressure ratio values simply because they started life as simple cycle engines, and were retrofitted with recuperators to take advantage of prevailing fuel economics.
4.1. Automotive Gas Turbine

Since the onset of automotive gas turbine development in the early 1950s, it has been stated many times that commercialization of the gas turbine for passenger car service always seems to be at least 10 years away (Harmon, 1982). In the last 40 years, the fuel economy and emissions of internal combustion engines have continued to improve, this giving the gas turbine a moving performance target. After many years of prototype demonstration the automotive gas turbine is still very much in the research phase (Boyd et al., 1987) with emphasis on very high-temperature operation, this necessitating extensive use of ceramic components, a key one being the high effectiveness rotary regenerative heat exchanger. The research program has set a thermal efficiency goal of 46% (i.e., specific fuel consumption of 0.30 lb/hp-hr). The aforementioned 10-year syndrome may well be optimistic, since it is unlikely that gas turbine powered automobiles will have an impact on the market until early in the next century. A step change in performance, offering a vehicle with say 100 miles/gallon capability would, however, attract industry attention. In the context of this paper, it is sufficient to say that when they are available, they will embody a high-temperature heat exchanger.

4.2. Military Tracked Vehicles

With its high-power density, ability to tolerate a wide range of fuels, and quick engine start characteristics (down to low temperatures), the gas turbine engine is ideally suited for modern tanks. The AGT 1500 engine, shown in Fig. 6, was selected for the U.S. Army M1 main battle tank (Harmon, 1986) and, to date, over 5000 units have been built and they have accumulated on the order of 1.5 million hours of operation. The selection of a 1120 kW(e) (1500 hp) recuperative engine (Engel and Anderson, 1971) assures good fuel economy, particularly at part power operation. Compared with previous diesel engines, the gas turbine exhibits quiet, vibration-free operation with clean exhaust. The recuperator (of modest effectiveness) is a prime surface design embodying multi-waveplates, which are welded together, the assembly being very amenable to volume production methods.

As mentioned previously, a higher specific power is realizable by including an intercooler; however, in the case of a tank engine, air cooling would be necessary, and the attendant high volumetric flow would give a bulky package (because of the large intercooler) which detracts from a major goal of high engine power density.
Programs continue on gas turbine technology for future tank propulsion, and studies have been reported by Duffy and Homer (1987) and Banthin and Deman (1988). Areas for improvement include lower fuel consumption (Zeybel, 1987), increased reliability/durability, continued reduction of acoustic, thermal, and smoke signatures, and, in the case of the recuperator, reduced size and weight, since it currently occupies about half the engine volume. Such technology advancements are important since alternate systems such as the rotary engine and adiabatic turbocompound diesel engines will ploy for use in tracked vehicles. Engines of lower power requirements than the main battle tank are well suited for tracked vehicles (Woodhouse, 1981, 1983) and an example of a modern compact gas turbine embodying a plate-fin recuperator is shown in Fig. 7.

Recuperator technology continues to advance and the CAT 5650 engine (Farmer, 1982), as shown in Fig. 8, is an example of a modern industrial engine embodying a high effectiveness, compact prime surface recuperator. Continued use of recuperated engines in the aforementioned power range is very much tied to the market place.

For applications where volume constraints are imposed on the engine and its fuel storage space, high-efficiency is paramount. Over the last 30 years, recuperative engines have had limited acceptance for marine propulsion, largely because of their poor reliability and bulkiness. Advancements in recuperator technology have now removed this impediment. The intercooled, recuperated engine (ICR) is particularly attractive for naval applications, the main attributes being (1) high efficiency, (2) good part load performance, (3) acceptable specific power, (4) reduced acoustic and thermal signatures, (5) compact power plant, and (6) potential for high reliability compared with combined cycle variants.
The intercooled, recuperative engine is by no means new as illustrated in Fig. 9. The RM 60 marine propulsion gas turbine (Preston, 1982) with two stage intercooling and recuperation, was operational in 1953. The concept was essentially ahead of its time, and it did not find acceptance then because of the control complexity and inadequate heat exchanger technology. In a much more compact package, an intercooled, recuperated, reheat gas turbine was demonstrated in the early 1960s to power a large truck (Hogg, 1963). Continuing vehicular gas turbine evolution, involving operation at very high temperatures, with ceramic components, quickly made this concept obsolete.

4.5. Large Gas Turbine for Utility Power Generation

With recuperator technology maturation, there is now a strong interest in the ICR concept as reported by Thomas and Higson (1985) and Thomson, Pratley, and Owen (1987). The marine ICR takes advantage of modern aircraft engine technology, and in the 19,000 to 22,000 kW(e) (25,000 to 30,000 hp) power range has the potential for efficiency levels in the low forties. The ICR is viewed favorably for main marine propulsion systems in the 1990s (Fogg, Nelson, and Pyatt, 1987), and as a candidate for shipboard auxiliary power (Mills and Karstensen, 1986). Recuperator and intercooler technologies are available today, and this will facilitate near-term development of this type of prime mover. With primary focus on marine propulsion, a fallout from this technology will be attractive variants for industrial applications.

4.6. Closed-Cycle Gas Turbines

The closed-cycle gas turbine, by its very nature, is heat exchanger intensive. A view is given on Fig. 10 of the largest machine running today, namely the 50 MW(e) Oberhausen 2 helium turbine plant in the Federal Republic of Germany (FRG). This plant, like the other fossil-fired units operated in Europe, utilized a recuperator, intercooler, and precooler; these exchangers being of tubular construction. The early experience with closed-cycle gas turbines involved the burning of dirty fuels and operation in a combined power and heat mode. These capabilities can be realized today with simple open-cycle gas turbines, and the future of fossil-fired closed-cycle gas turbines for terrestrial applications is rather uncertain (McDonald, 1987). The closed-cycle gas turbine may find acceptance with a nuclear heat source for specialized defense applications. For space power systems with power sources in the range of tens to hundreds of kilowatts (Tillett et al., 1988) the Brayton cycle, coupled with a gas-cooled reactor, is attractive. Another potential application for the nuclear closed-cycle gas turbine is for future submarine propulsion (McDonald, 1988). For these two applications, the imposed constraints on overall plant weight and volume pose a challenge to the heat exchanger designer.

4.7. Propulsion Opportunities

The remaining bastion of gas turbine technology to take advantage of heat exchangers is the propulsion field. This is not meant to refer to large turbo-fan engines, but rather turbo-shaft engines rated up to about 1492 kW (2000 hp) for helicopter propulsion. The only recuperative propulsion engine demonstrated was a...
modified T63 engine (Privonnik, 1968), as shown in Fig. 11, and with a "bolt-on" tubular recuperator, the range of the helicopter was increased by over 25%. Following this, a study was performed (McDonald and Langworthy, 1971) on an engine design concept with an integrated recuperator, but it did not find acceptance in an era of low fuel cost.

![T-63 Helicopter Engine - Only Recuperative Propulsion Engine to Have Been Demonstrated](Fig. 11 T-63 Helicopter Engine - Only Recuperative Propulsion Engine to Have Been Demonstrated (Courtesy GM Allison Gas Turbine Division))

Simple cycle engines for helicopter propulsion have made significant performance improvements over the last 20 years, but further efficiency advancements are likely to be incremental. Operating with high-pressure ratios, and very high turbine inlet temperature, attractive values of specific power (i.e., kW/kg/s) have been realized. The result has been to minimize blade heights to the point where Reynolds number, tip clearance effects, and surface roughness influence the blading efficiencies. Further increases in both compressor and turbine efficiency will surely be realized, but they will likely be incremental. The aforementioned is essentially a preamble to the effect that substantial increases in efficiency for small engines will only be possible by utilizing a recuperator (and perhaps an intercooler), or by considering compound adiabatic diesel engines (Wilsted, 1982). The highest efficiency value of 54.8% (corresponding to an SFC of 0.252 lb/hp-h) shown in Fig. 5 is for an advanced technology 187 kW (250 hp) propulsion engine concept utilizing a rotary regenerator and intercooler (Mock, Caldwell, and Boyd, 1984). In the very small engine size, the possibility of a recuperated prop fan concept for ultra long-range cruise missile propulsion warrants study. The future of the recuperated engine for helicopter or aircraft propulsion is very much tied to fuel economics and mission profile. The heat exchanger technology for this application is available today in the form of compact, lightweight, prime-surface recuperators (tubular and formed plate types) with proven structural integrity.

5. HEAT EXCHANGER TECHNOLOGY

5.1. Intercooler

Operating at rather low pressure and temperature levels, the air-to-water intercooler is regarded as a conventional industrial heat exchanger. Having single-phase fluids with attendant modest heat transfer coefficients, large surface areas are required. Tubular geometries are desirable to provide both water side cleaning capability (to remove fouling products), and individual tube-plugging means in the event that a leak develops. For each application detailed design studies are necessary to establish optimum configurations (i.e., helical bundle, straight tube, U-tube, etc.), but in each case enhanced surface geometries will be necessary to minimize the surface area. Candidate surface geometries include finned-tubes, dimpled tubes, spiral geometry, surface roughness, etc. A major goal is to minimize the size of the intercooler so that it is compatible with the compact nature of the gas turbine prime-mover. The ultimate intercooling concept would be to utilize the compressor stators to remove the compression work, perhaps by means of heat pipes.

5.2. Recuperator

The selection of surface geometry is rather application dependent, and the differing types available will yield units of varying proportions in terms of frontal area and flow length. The quantity of units to be produced could strongly influence whether welded or brazed assemblies be utilized. The dominant requirement for high effectiveness and low pressure loss essentially implies a counter-flow configuration. Heat exchanger designers today can take advantage of a large heat transfer and friction data base accumulated over several decades (Kays and London, 1984). It is not the purpose of this paper to select recuperator types for particular applications, but it is germane to mention that a wide range of surface geometries, and construction configurations are available for user evaluation/selection. The major types of recuperators include the following: (1) plate-fin (Kretzinger, Valentino, and Parker, 1982), (2) prime surfaces (Jen, 1987, and Parsons, 1985), (3) plain tubes (Kind and Ruhe, 1977, and Diesel and Gas Turbine Worldwide, 1984), (4) enhanced tubes (Gas Turbine World, 1978), and (5) finned tubes (Nakhamkin et al., 1986). With increasing emphasis being placed on engine-heat exchanger size compatibility, it can be projected that plain tubular geometries (yielding volume-intensive units) will not be featured prominently in the future. A variant featuring a fluted-tube geometry (Yampolsky, 1981) may be considered, since it has attractive heat transfer-to-friction characteristics, and offers enhancement on both the air and gas sides of the unit.

The status of major elements of recuperator technology is highlighted on Table 1. The major issue from the gas turbine user's standpoint relates to the integrity and reliability of the recuperator, since these have been major impediments for their deployment in the past. To minimize thermal stresses induced during transients, as a result of metal temperature differential, modern recuperator matrices are designed to achieve thermal inertia compatibility between the separating plates and the seals, and the parts attached to the core. The plate-fin and prime-surface recuperators in service today have demonstrated satisfactory structural integrity for very demanding service conditions. Other concerns that have been raised in the past, including fouling (Bowen et al., 1982), (Bodman and Priore, 1988) and fires (McDonald, 1969) are well understood today, and have been factored into the design process. Existing metallic alloys can...
accommodate the temperature levels experienced in the recuperators in today's engines. Wrought alloys, such as Incoloy 800 and Inconel 617, have the capability for increased temperatures, and in the long-term ceramic recuperators, now in the early stage of development, will surely be utilized (Bliem, 1985).

Table 1 Gas Turbine Recuperator Technology Status

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<th>CONSIDERATIONS/ISSUES</th>
<th>SOLUTIONS/COMMENTS</th>
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| PERFORMANCE           | • Advanced heat transfer surfaces available  
                        • Effectiveness levels of over 93% realizable  
                        • Overall pressure loss of less than 3% possible  
                        • Recuperator major contributor to high engine part load efficiency |
| HEAT EXCHANGER SIZE & WEIGHT | • Compact prime and secondary surface geometries available  
                              • Exchanger can be integrated with gas turbine  
                              • Challenging power densities for regular applications demonstrated |
| STRUCTURAL INTEGRITY & LIFE | • Cracking and leakage from thermal stress is still a problem in some units  
                              • Sophisticated analytical methods have resulted in a better understanding of high temperature transients  
                              • Contemporary designs compatible with cyclic environment  
                              • 109,000 hour life realizable |
| ENVIRONMENTAL EFFECTS (i.e., Fouling, Corrosion, Erosion) | • Advanced combustion systems have alleviated fouling concerns  
                              • Modern separation and filtration systems minimize effect of sand and salt injection  
                              • Advanced control systems operate matrix flow concerns |
| FABRICATION AND COST | • Prime and secondary surface concepts available to highly automated, volume oriented manufacturing processes  
                          • Standardized modules established  
                          • Short pay-back periods realizable |
| SERVICE | • Contemporary designs facilitate ease of inspection and repair  
           • Modules readily replaceable  
           • Retrofit appropriate with improved units can be achieved |
| LIMITATIONS | • Limited temperature growth capability exists with existing wrought alloys  
               • Ceramic units demonstrated for ultra high temperature operation |
| INSTITUTIONAL | • Fundamental resistance to heat exchangers being overcome as advancements in plant thermal efficiency become harder to realize  
               • Technology available and demonstrated  
               • Several recuperator options available to users |

5.3. Steam Generator

Steam generator technology is well established, and the thermodynamic conditions associated with gas turbine operation can be readily accommodated. Units operational today are based on establishing a basic module that can be packaged to accommodate a wide range of engine sizes. To establish a steam generator assembly that is compatible with the compact nature of the gas turbine itself involves the utilization of finned-tube geometries, together with a once-through boiling system. This type of unit has been demonstrated (Smith, 1988) and an example of a compact steam generator assembly is shown in Fig. 12. The attributes of a once-through steam generator are highlighted on Table 2. With increasing emphasis being placed on both combined cycle operation and steam injected gas turbines, the utilization of steam generators will become a major factor for industrial gas turbines.

5.4. Other Heat Exchangers

The majority of the remaining heat exchangers shown on Fig. 4 are of conventional types and, while perhaps not available directly off-the-shelf, they represent types of construction that are used extensively in the power generation industry. The one heat exchanger that has demanding requirements is the in-bed unit associated with the pressurized fluidized bed combustor (PFBC) gas turbine. Operating in a high-temperature environment with corrosion and erosion as major factors, units are operational today, but they are considered to be beyond the scope of this paper.

Fig. 12 Compact, Finned-Tube, Once-Through-Boiling Heat Recovery Steam Generator for Industrial Gas Turbine (Courtesy Solar Turbines, Inc.)

Table 2 Attributes of Once-Through Steam Generator

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<th>ADVANTAGES</th>
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<tbody>
<tr>
<td>• Compact exchanger assembly</td>
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<tr>
<td>• Low weight system</td>
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<tr>
<td>• Simple construction with minimum number of parts</td>
</tr>
<tr>
<td>• Low water inventory</td>
</tr>
<tr>
<td>• Simple piping arrangement</td>
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<tr>
<td>• Low cost (no drums and recirculation pumps)</td>
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<tr>
<td>• Steam production a simple function of feedwater flow</td>
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<tr>
<td>• Stable operation over wide range</td>
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<tr>
<td>• No blow down necessary</td>
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<tr>
<td>• Responsive to system transients</td>
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<tr>
<td>• Structural integrity assured if unit run in dry condition</td>
</tr>
<tr>
<td>• Well established technology base</td>
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<table>
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<tr>
<th>INHERENT CONSIDERATIONS</th>
</tr>
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<tbody>
<tr>
<td>• High feedwater quality necessary (chemistry control)</td>
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<tr>
<td>• Individual tubes must be orificed (high pressure loss)</td>
</tr>
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<td>• Sophisticated control system needed</td>
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6. SUMMARY

It is realistic to project that the gas turbine will become a major prime-mover across the full spectrum of power applications early in the 21st century.
Performance advancements will continue, of course, the major contributor perhaps being ever increasing values of turbine inlet temperatures towards the ultimate stoichiometric value of $1650^\circ$ to $2200^\circ$C ($3000^\circ$ to $4000^\circ$F). To realize thermal efficiency values in excess of about 35%, advanced cycles will utilize heat exchangers in one form or another. A major theme in this paper has been that within the last decade, heat exchanger technology advancements have kept pace with the gas turbine industry, and units such as the intercooler, recuperator, and steam generator are available for commercial service today.

The extent to which heat exchangers are utilized is marketplace-dependent and, in times of low oil and gas prices, it is understandable that current interest is modest. In applications supportive of meeting defense needs the utilization of heat exchangers can be viewed in a different light, particularly those involving fuel logistics concerns. The intercooled, recuperative engine offers high specific power (by utilizing high compressor pressure ratio) and low fuel consumption (impact of high effectiveness heat exchanger). Initially being developed for defense applications, this engine should find acceptance for industrial service.

Since heat exchangers still occupy a considerable percentage of the overall engine volume, continuing demands will be placed on thermal specialists to reduce their size, weight, and cost while, at the same time, assuring that reliability goals be met. Existing materials can be used for the range of heat exchangers discussed (Fig. 13). As temperatures continue to increase, there will be a natural transition to ceramic and composite (e.g., carbon/carbon) recuperators as the technology matures. While rather sadly neglected to date, it is hoped that recuperative turboshaft engines for propulsion will become a reality before the end of this century (Pletschacher, 1987).

![Fig. 14 Projected Increased Use of Heat Exchanged Gas Turbines](https://asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1989/79160/V004T09A005/4456706/v004t09a005-89-gt-103.pdf)


