GAS TURBINE REACTORS – CHEMICALS, HEAT & POWER

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ABSTRACT

Gas turbines are routinely used for generating power and heat, (CHP), and increasingly, a proportion of the heat from the gas turbine exhaust is used to provide refrigeration or air conditioning - combined heat, power and cooling. One may add another useful output - chemicals. By utilising one or more of the components within a gas turbine cycle as a reactor, we may potentially use a range of feedstock to produce chemicals - the Gas Turbine Reactor.

The components we might consider include the combustion chamber as a reforming reactor, blades as reactors, providing cooling of the metal as well, recuperators as heat exchanger-rectors and intercoolers having the same role. The chemical or gas turbine engineer may well think of other opportunities in either open or closed cycle machines.

This paper discusses some of the above options, drawing in part upon gas turbine blade cooling technologies and upon recent developments in the UK and elsewhere in HEX-Reactors - units combining reactions and heat exchange on one or more sides of a compact heat exchanger.

KEYWORDS

Gas turbines, reactors, blade cooling, heat exchanger-reactors.

1. INTRODUCTION

Prime movers of all types, ranging from Stirling engines and micro-turbines to Multi-MW reciprocating engines and aero-derivative gas turbines, are becoming increasingly used for providing heat and power – combined heat & power. In a number of instances, where air conditioning and/or refrigeration is a priority, such machines can also provide cooling, either via a heat-driven absorption machine, or indirectly, providing electricity to power vapour compression cycles. Such combinations are routine in large-scale applications. An additional characteristic of prime movers, in particular gas turbines, is the opportunity to use them as chemical reactors. Thus the prime mover additionally becomes a chemicals factory.

Two examples are intercoolers and turbine blade thermal control. The intercooler on a multi-stage compressor of a gas turbine is a heat exchanger used to cool the working fluid (e.g. air) between compression stages, increasing the efficiency. Intercoolers are heat exchangers, and in more recent times have been selected from a range of compact types. Compact heat exchangers are also used as heat exchanger-reactors (HEX-reactors), where one or more sides may be coated with a catalyst, to allow a reaction to take place there. This suggests that one might examine the feasibility of using the compact intercooler as an endothermic reactor, with the heat removed from the compressed air by this reaction. At the same time, a useful chemical product could result from the reactor side of the intercooler. One may envisage exothermic reactions taking place in reheaters, too. Those familiar with chemically-recuperated and other more exotic gas turbine cycles will recognise the basis for these concepts.

Another challenge to gas turbine manufacturers in their search for improved efficiency centres on turbine blade life at high temperatures. Blade cooling by air, steam etc. is an approach which can overcome the need to use ceramics – but it has its limitations, in terms of heat transfer coefficients. Although improvements are being made, and a scan of recent patents confirms the efforts being made in this direction, a more radical approach to blade thermal control may be needed. The second example is thus the use of a catalyst on or inside the blade, to again carry out a reaction which will cool the external blade surface, without adversely interfering with the blade geometry/performance. Blade cooling is discussed first below.

2. BLADE COOLING

The concept of blade cooling using an endothermic reaction, which in turn might be used to produce a useful by-product, was one of the first pointers to the gas turbine reactor. It s of interest to examine other blade cooling techniques before briefly discussing the reaction method, however.

Blade cooling using liquid or change-of-phase systems is not a new concept, having been introduced when turbine inlet temperatures were significantly lower than they are today. Holzwarth (1) introduced the concept of using a thermosyphon to cool blades as long ago as 1938. It was recognised that centrifugal accelerations were of the order of 10^4g suggesting that density variations in a rotating fluid may be expected to give rise to substantial natural circulation velocities. Thus, if a turbine blade is first hollowed and then filled with a fluid, any heat transferred to the blade from the hot gases will be conducted into the fluid, thereby introducing radial buoyancy forces.

One system was tested by Schmidt (2) in the 1950s. This is an open thermosyphon in which thermal buoyancy forces give rise to a convective flux towards the blade root. The heat is then removed either by removing the coolant without phase change, or by evaporation at the coolant's free surface (as in a two-phase heat pipe or thermosyphon – but the system remained open). Water was used, operating close to its critical point, and showed that turbine inlet temperatures of at least 1200^{o}C were feasible.

The open system was found at the time to have a number of disadvantages – large internal hydrostatic pressures, vibration from coolant instability around the root, and blockage due to fouling (oxidation).

The alternative option was to use a closed thermosyphon system – like a heat pipe. This permitted control of oxidation (as the system was sealed and purged of air), and allowed separation of the primary and secondary coolants. Liquid metals could be used here as the primary coolant, as in sodium-filled valves. In practice, a sodium-potassium eutectic (NaK) was used, and gave much cooler blade temperatures than the open system of Schmidt. Water cooling was applied at the blade root. A patent survey reveals that Rolls-Royce was recently interested in high temperature heat pipes for blade cooling.

Blade cooling also featured in the 'Advanced Turbine Systems Programme – Conceptual Design and Product Development', supported by the US Department of Energy, (3, 4). The aim of this programme is to provide a product development plan for an 'ultra high efficiency, environmentally superior and cost competitive industrial gas turbine…'

Air remains a popular method of cooling GT blades, and many patents and studies relate to the use of this medium. Heat transfer enhancement techniques are routinely considered, such as discrete ribs inside the blade passages, (5), with an increasing demand for this type of research.

So-called vapour cooling of GT blades is the subject of a patent assigned to Hitachi (6). The vapour used to cool the blades (which does not change phase as it passes through the blades) is supplied through a central passage in a rotor and the vapour, having passed through the blades, is returned to a second passage in the rotor. The patent suggests that first and second stage blades, at least, could be cooled using this technique.

In an earlier patent (7) Hitachi used as the source of the blade coolant some of the air from the final stage of the compressor. However, this air was treated with a water spray to cool it before it entered the turbine blade inner passages. The presence of droplets also enhances cooling by evaporating.

Recuperative steam cooled gas turbine: The Schmidt double turbine concept discussed earlier was one approach to beneficially using the energy extracted by the blade coolant stream. Westinghouse Electric (8) has proposed to use the coolant, which is both delivered to, and extracted from, the blades in the form of steam, to aid combustion and NO_x reduction by using it as injected steam. It also improves power output.

Blade cooling with endothermic fuel: The patent filed in 1991 by the United States Air Force comes close to the concept which allowed the subject of this study to germinate. As described in (9), the USAF proposed a hollow GT turbine rotor blade with a catalyst coated on the inner surface. The cooling would be effected by vaporisation and decomposition of an endothermic fuel introduced into the hollow blade. The schematics in *Fig. 1 (a & b)* taken from (9), show injection of the fuel into the core of the rotor blade, from where it is directed onto a catalyst coating the inner surface of the blade. The endothermic fuel can be methanol, JP7, n-heptane or methylcyclohexane - all liquids. The decomposition products are gases, and may be burnt as fuel.

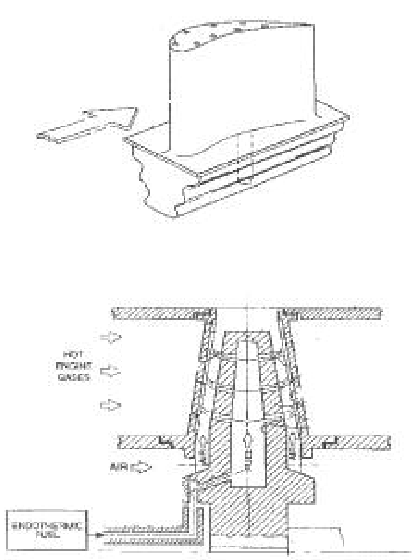

Figure. 1. Exothermic fuel injected into a turbine blade for cooling

UTC (10) takes the above concept a little further by introducing a catalytic reaction to cool heat sources on high speed vehicles. The concept is effectively based on a product reactor, the catalyst being selected to produce hydrogen and unsaturated hydrocarbons that are used to cool the stream serving the heat-gaining components. The catalyst is designed for a conversion rate of greater than 60%, producing a total heat sink of about 1.3 kW/kg fuel. The fuel stream contacts the catalyst at a rate (liquid hourly space velocity) of 10 h^{-1}.

Allied-Signal Inc. (11) later filed a derivative of this, in which a series of heat exchangers, each containing a reaction portion, are linked, on the other side being a heat source stream. This stream is of course cooled by the endothermic reaction, and the cooled stream is used to remove heat from critical components in hypersonic vehicles. After reheating, the cooled fluid is passed to the combustor.

None of these cooling systems make true use of the reactant as a chemical product, although the US Air Force concept comes close. What might be envisaged is an endothermic reaction, such as one of the catalytic dehydrogenations, although these take place generally at lower temperatures, more appropriate to the intercooler heat exchanger-reactor, as discussed below. There have been concepts studied for catalytic reactions on the outside of the turbine blade to effect cooling, but chemical recovery would be difficult.

3. INTERCOOLING

In gas turbines in which compression is staged, it is possible to incorporate intercoolers – heat exchangers – between the compression stages to remove the heat of compression from the partially compressed air. The effect of intercooling is particularly beneficial on gas turbines with high compressor pressure ratios. The cycle shown in *Fig. 2* incorporates an intercooler and other efficiency-boosting heat exchangers.

The heat rejected in an intercooler is often taken to a cooling tower, adding to plant capital costs, but leading to no useful duty for the rejected heat.

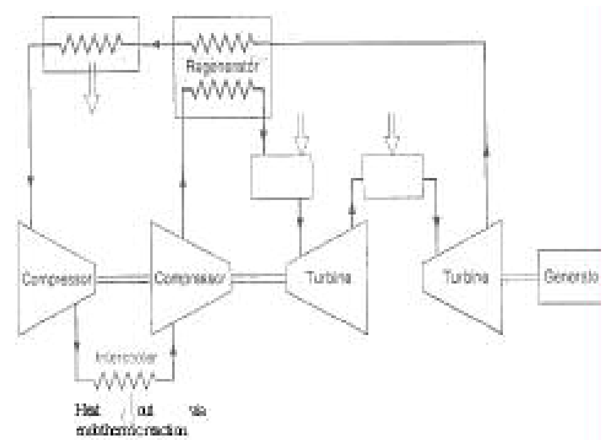

Figure 2. An intercooler with an endothermic reaction in a heat exchanger - reactor

An invention assigned to the California Energy Commission in the USA, (12), proposes at least one way in which the rejected heat in the intercooler can be usefully employed. One role is to use the heat exchanger as part of a reheat cycle. Alternatively, the intercooler heat can be used via a second high pressure heat exchanger to heat methane(fuel)/water mixtures, generating a fuel/steam mixture for injection into a low NO_x combustor.

Some work has been proposed on isothermal intercooling (13). This involves removing the heat at each stage of compression via the stator blades. A study has been carried out at the University of Genova in Italy. A refrigerant was used inside the stator blades, and 100% intercooling was assumed in each stage. The results were not particularly encouraging, for a number of reasons:

- The air side heat transfer coefficient was low
- The air side (stator) surface area was inadequate
- The stators in the selected GT were so thin that internal passages were difficult to incorporate (compared to that feasible in turbine blades).

The main benefit was in a significant decrease in compressor power, giving a very high specific power output (kW/kg.s).

The use of heat exchanger-reactors (HEX-reactors) instead of solely an intercooler heat exchanger may make the required breakthrough to chemicals production in this area of the GT. Employing plates such as those illustrated in *Fig. 3*, used by Chart Heat Exchangers Ltd. in their HEX-reactors, a heat exchanger structure may have a reaction taking place on one or both sides, depending upon the location of catalytically-coated surfaces.

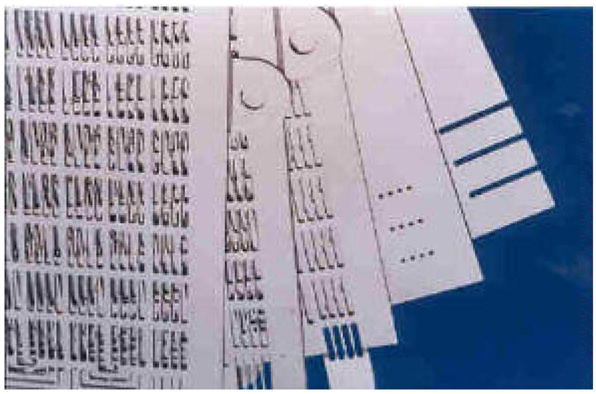

Figure 3 : Plates used in the Chart Heat Exchanger Reactor

Intercooling duties suggest that useful cooling of the compressor gas could be undertaken with catalytic dehydrogenations (endothermic reactions) taking place at temperatures in the range 500-600 K. Although there must be an examination of the equilibrium thermodynamics versus the kinetic limitations for each reaction, the types of chemicals involved might range from the production of benzene from aromatic compounds to the dehydrogenation of -OH groups to form ketones.

4. SOME OTHER CONCEPTS

There are a number of other concepts which should be mentioned, which may have some future impact on the gas turbine reactor.

Gas turbine + fuel cell: US patent 5693201 (14) describes a turbine system with a fuel cell located between the compressor and turbine. Data obtained to date suggest that the compressor is used to raise the pressure of one medium which is fed to the fuel cell, the second medium being fed directly into the cell. The electrochemical reaction, as well as producing electricity, gives a sufficiently high exhaust gas temperature to allow the reject gases to be expanded through a turbine, driving the compressor. The concept is variously described as an 'electrochemical combustor-replacement (ECCR) or as a fuel cell for combustor replacement (FCCR).

An earlier patent from the US Department of Energy describes a different approach to linking fuel cells and gas turbine cycles, (15). An indirect-heated GT cycle is bottomed with a fuel cell cycle, the heated air from the turbine being used to directly heat the fuel cell cathode. The hot cathode recycled gases provide a substantial part of the heat required for indirect heating of the compressed air used in the GT. A separate combustor provides the balance of the heat needs. Hot gases from the fuel cell reduce the GT fuel needs and also the NO_x emissions. Residual heat from the fuel cell may be used in a steam cycle or for absorption cooling.

Fuel cell-gas turbine combinations are becoming of increasing interest in 2001, but are less relevant to chemicals production.

Reforming and reheat combusting in a GT: In this system (16) a mixture of steam and a combustible 'effluent' such as methane is reformed or partially oxidised to produce a hydrogen-rich fuel. This fuel is then used for primary combustion and also for reheat upstream of the final turbine stage. The reheat is effected by injection of the hydrogen through cooling orifices of the first turbine upstream of the final turbine stage, and/or from the trailing edges of the stationary vanes or rotating blades. This allows auto-ignition.

The patent also proposes that the hydrogen-rich fuel can be used for blade cooling before re-injection.

Reforming using exhaust heat: Perhaps the most obvious and least exciting way of using a gas turbine as a reformer is to use the exhaust heat downstream of the power turbine. The GE proposal covers this (17), the reformer producing fuel for the combustion chamber. Additionally, other means for heating the reformer are proposed.

5. CONCLUSIONS

The gas turbine may be combined with a number of useful reactions which can benefit the turbine cycle and potentially produce useful chemicals.

It is possible that the production of chemicals, heat and power within the same unit - a gas turbine - can find a niche market within the petrochemicals sector of industry.

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