International Journal of Air-Conditioning and Refrigeration Vol. 16, No. 1 (2008) 30~36

Various Heat Exchangers Utilized in Gas-Turbines for Performance Enhancement

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(Received January 14, 2008; Revision received March 10, 2008)

Abstract

Modern world takes advantages of gas-turbines for various purposes. Most of gas-turbines incorporate various heat exchangers in order to achieve specific functions and enhance thermal efficiency as well. This paper reviews heat exchangers that had been used, currently being used, and under development for the future application in various kinds of gas turbines. The heat exchanger matrix configurations and manufacturing methods depend on where they are applied. This review work shows that the recent advancement in heat exchanger technologies makes it possible to develop intercoolers and recuperators for large gas turbines as well as micro gas turbines.

Key words: Heat exchanger; Gas-turbine; Recuperator; Intercooler

1. Introduction

Since Ægidius Elling built the first gas turbine in 1903 which could produce more power than needed to run itself, engineers and scientists have made a huge progress in gas-turbine design. In the modern world the gas-turbines are widely used for electric power generation, fluid pumping, and vehicle propulsion. Especially, aero gas-turbines or jet-engines continued to be developed and dominantly used for airplane propulsion since Frank Whittle invented the design for a gas turbine for jet propulsion in 1930.

Gas-turbines are composed of numerous parts. Some of them should experience a rotational movements and some of them are exposed to hot or cold environments. Due to these facts, modern gas-turbines incorporate many heat exchangers such as fuel cooled oil cooler, air cooled oil cooler, air cooled fuel cooler, power electronic cooler, and fuel cooled cooling air cooler.

The gas-turbines take advantage of fossil fuel to produce power. They inherently exhaust gaseous emissions including carbon dioxide and nitrogen oxides (NOx). The gaseous emissions as well as noise emission problems have been cited with respect to gas-turbines after scientists gave proof of global warming. It is worth noting that reductions in gaseous emissions are directly related with fuel consumption and, thus, impact operation costs. Gas-turbine procurers and environmental issues require gas turbine vendors to produce environment friendly gas-turbines with lower emissions and higher specific fuel consumption (SFC) ratings. The requirements can be met if heat exchangers are incorporated into gas turbines. Recuperators can increase the gas-turbine cycle efficiency by recovering heat from the hot exhaust gas. Intercoolers reduce the work required to compress air between two successive compressors, hence they increase the net work output. Some parts of combustion chamber and turbine necessitate cooling air in order to withstand the hot exhaust gas. Cooling the cool air further may allow a higher turbine entrance temperature and can reduce the compressed air bleed. Cooled cooling air can provide benefits that include an increase in turbine efficiency as well as the creation of additional air for combustion. All these functions - recuperation, intercooling, and cooling air cooling - can be only achieved by heat exchangers. Fig. 1 shows schematics of the Brayton cycle with intercooler, recuperator, and cooling air cooler.

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McDonald and Wilson(1) discussed gas-turbine efficiency trends in terms of the turbine-entrance temperature, compressors and turbine efficiencies, and the future role of exhaust-heat-recovery exchangers. Ten years ago, they predicted that within two decades, heat exchanged engines would be in the mainstream of gas-turbine applications. This projection proved correct, as many land-based and marine gas turbines are presently equipped with recuperators and/or intercoolers. For instance, GE has developed intercooled gas turbines for power plant applications with its marketing of the LMS100 model, a 100MW aero-derivative gas turbine. Northrop Grumman/Rolls-Royce has also produced the marine-propulsion gas turbine system WR-21 incorporating both intercoolers and recuperators. This engine has an output power of approximately 25 MW and an efficiency of 43%.

Intercoolers and recuperators are currently used in land-based and marine propulsion gas turbines. However, no civil aero jet engines incorporating a recuperator or intercooler exist thus far. The intercooler and recuperator for a gas turbine should be functioning in a high temperature and high pressure environments. This harsh operating condition may cause problems such as corrosion and mechanical integrity failure. The issues and state-of-the- art technology concerning high temperature heat exchangers have been recently reviewed by Sunden.(2) Investigations in this area include the heat exchanger matrix design, material selection, and manufacturing technologies and optimizations. This type of research has been carried out worldwide, as the benefits of intercooling and recuperation are universally recognized. The authors reviewed previous literature in this area and summarize heat exchangers applicable to gas turbine intercooler, recuperator, and cooling air cooler in terms of matrix design and materials for them.

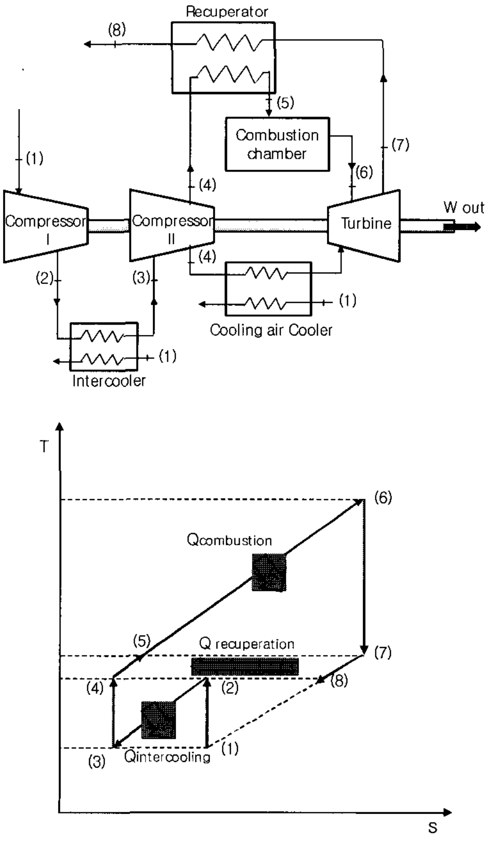

Fig. 1. Brayton cycle with intercooler, recuperator, and cooling air cooler.

2. General heat exchangers

The most common heat exchangers used in modern industry are shell and tube heat exchangers (STHE). The technologies for STHE design and manufacturing are well established and standardized. The Tubular Exchanger Manufacturers Association (TEMA) provides standards for SHTE part naming, classification, manufacturing, installation and maintenance.(3) STHEs are utilized in the V2500 and RB211 engines as fuel-cooled oil coolers.

A common type of compact heat exchanger is a plate-fin heat exchanger (PFHE). Various pin designs have been developed, among these the plain, slit, louver, offset strip, wavy, and perforated fins.(4) PFHEs are mainly used where a heat transfer between a liquid phase and a gas phase occurs. The gas phase flows through the fin side, as the convective heat transfer coefficient of a gas flow is lower than that of a liquid flow. It is typical that a PFHE is more compact and lighter compared to a STHE. Some jet-engines utilize a PFHE as an air-cooled oil cooler or as an air-cooled integrated drive generator (IDG) oil cooler. The intercooler and recuperator cores of WR21 are also PFHE-type cores.

3. Cooling air cooler

Three types of heat exchanger applications directly influence gas turbine efficiency: intercoolers, recuperators, cooling-air coolers. Information regarding heat exchangers for cooling-air cooling was rare in the open literature. The Russian AL-31F engine was developed by Lyulka in the mid-1970s for fighters,

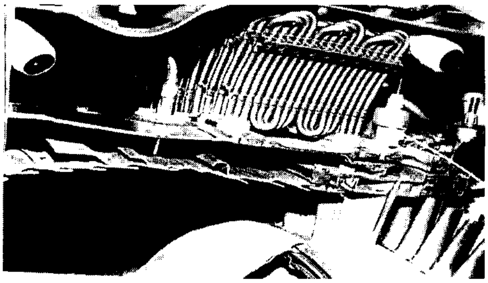

Fig. 2. AL-31F engine with cooling air cooler.

which incorporates cooling air cooler. A tubular heat exchanger serves as the cooling air cooler of Lyulka AL-31F engine as shown in Fig. 2. However, no known civil engine incorporates it as yet. The utilization of a cooling-air cooler thus requires further study. In order for cooling-air coolers to be utilized, genuine benefits should be first shown through sophisticated gas-turbine system analyses.

4. Recuperators

Recuperative heat exchangers have long been studied and utilized in power and marine propulsion applications. The influence of recuperators on microturbine efficiency and their use as potential heat exchangers have been discussed by McDonald(5). As a result, various types of heat exchanging matrix configurations have been suggested. This includes the plate, plate-fin, fin-tube, spiral, and annular configurations. Utriainen and Sunden(6) reviewed the applications and types of recuperators used in gas turbine units. After their review, there has been progress in recuperator development.

Plate heat exchangers (PHE) are made of a corrugated plate stack. A PHE is also known as a primary surface-type heat exchanger, as the plates separate fluids and the heat transfer occurs directly across the plates. The plates of a PHE generally have patterns. The patterns may be cross-corrugated(7,8), cross-undulated(9,10), or cross-wavy(10). These plates may be bolted, welded, or brazed. Plate heat exchangers are widely used in modern industrial processes where operating temperatures and pressures are relatively low. A number of manufacturers, however, have designed PHEs for gas-turbine applications. RSAB developed a completely welded primary surface recuperator for application to a micro gas turbine (MGT) power plant for combined electricity and heat generation(11). Fig. 3 shows the external shape and plate corrugation pattern of this recuperator. Compressed air enters the manifold and distributes through channels established between adjacent corrugated plates. The exhaust gas flows through the matrix in a counter-flow manner. Similar designs, such as the RSAB primary surface counter-flow recuperator, have been developed by Ingersol Rand for applications to MGT(12). The manufacturer claims that this recuperator exploits the best aspects of both primary and extended surface plate heat exchangers while overcoming their inherent weakness. Thus, it is marketed as tolerable to the severe thermal gradients that often occur during transient operation. Fig. 4 shows a PFHE that was developed for a recuperated gas turbine engine for ship propulsion named super marine gas turbine(SMGT)(13). The external shape of the matrix appears similar to the RSAB primary surface counter-flow recuperator; however, this heat exchanger accommodates offset fins.

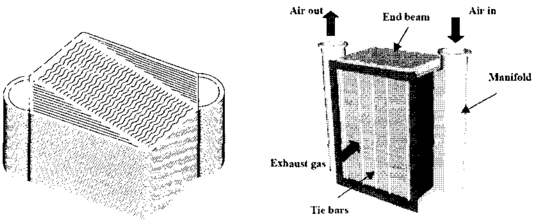

Fig. 3. PHE recuperator by RSAB.

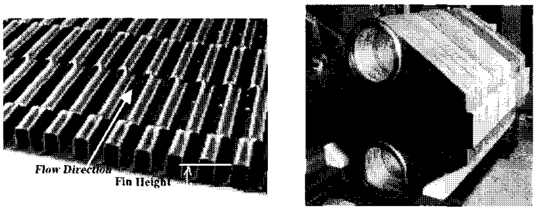

Fig. 4. PFHE recuperator for SMGT

The annular recuperator, another primary surface-type heat exchanger, is utilized in microturbine electric generators(14-16). This annular recuperator is comprised of hundreds of air cells, as shown in Fig. 5. Each air cell is fabricated by welding fin-folded stainless steel sheets. The Oak Ridge National Laboratory (ORNL) modified a micro-turbine to achieve recuperator inlet gas temperatures as high as 850℃.

ACTE developed a primary surface-type spiral heat exchanger (SHE) for application to recuperated gas turbines.(17) Fig. 6 shows the external shape and a cross-sectional view of its flow channel. Flat plates and corrugated plates alternate in a stack. The fluids enter, spread, and exit the heat exchanger in a counter-flow manner. The corrugated spiral plates

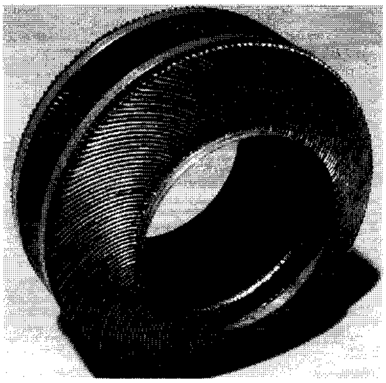

Fig. 5. Annular recuperator.

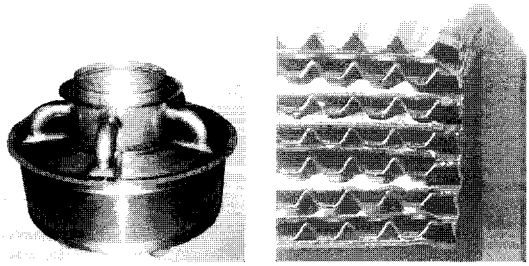

Fig. 6. ACTE Spiral primary surface.

create turbulence to enhance the heat transfer. It also provides contact points that can enhance structural integrity. Another spiral recuperator was developed by Rolls-Royce. The matrix configuration and ducting for this heat exchanger is illustrated in Fig. 7. Perforated extended fins are inserted between two roles of dimpled metal sheets. The advantages are that it reduces the stresses and thermal gradients compared to flat-plate configurations. Air is introduced into the centre of the heat exchanger core, while the gas is counter-flowed.(18,19)

An increase in turbine entrance temperature has forced ceramic materials to be considered in recuperator manufacturing. Fig. 8 shows a compact plate-fin ceramic recuperator module fabricated by Allied/Signal in the late 1970s for a cruse-missile application.(20) Ceramic heat recuperators were developed for application to an automobile hybrid gas turbine.(1) Recent literature shows that a recuperator design is being investigated using new ceramic materials and manufacturing techniques as material and manufacturing technologies advance. Cermatec Inc utilized laminated object manufacturing (LOM) methods to develop a compact ceramic recuperator for use in high temperature microturbines as shown in Fig. 9.(21)

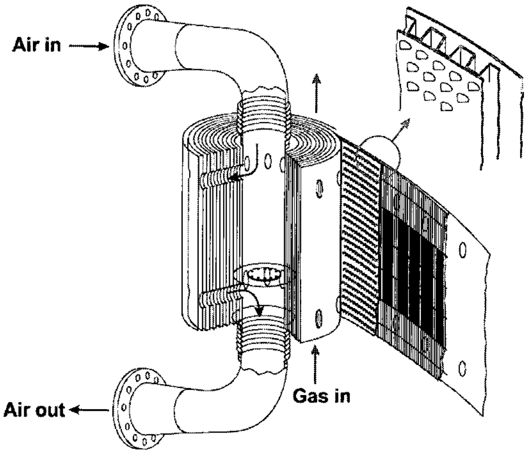

Fig. 7. RR spiral heat exchanger with perforated fins.

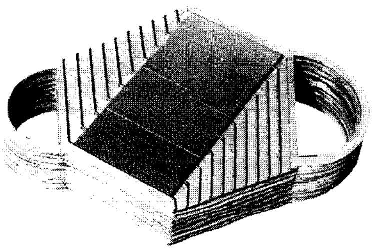

Fig. 8. Ceramic plate-fin recuperator developed by Allied/Signal.

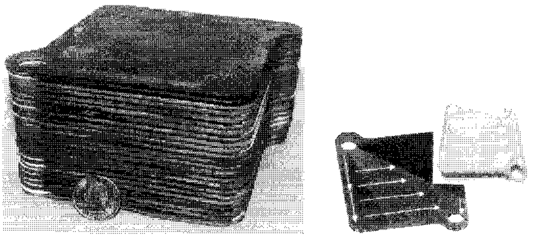

Fig. 9. Ceramic micro-channel gas turbine recuperator element and module by Cermatec Inc.

The aforementioned recuperators were originally developed for application to micro gas turbines. Therefore, the operating conditions would be relatively mild. In particular, a high-pressure capability of up to 30 bar is not needed, as is required by medium or large aero-derivative gas turbines. The recuperator utilized in WR-21 is a counter-flow plate-fin heat exchanger (PFHE) made of high-grade stainless steel. This PFHE operates in an environment where temperature increases to 575℃ and where the temperature difference between the top and bottom of the PFHE is 300℃. A recent noticeable improvement in the development of heat exchangers for application to

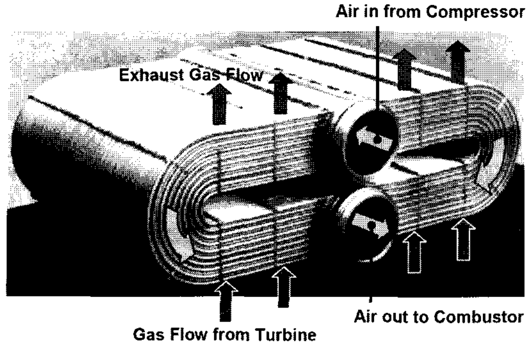

Fig. 10. MTU profile tube heat exchanger for recuperation

recuperated aero gas-turbine engines was made by MTU(22). It has developed a new heat exchanger consisting of a bundle of profile tubes, as shown in Fig. 10.(23) This heat exchanger has a compact cross-counter-flow configuration. However, the total weight of the recuperator system including the heat exchanger matrix and ducting was estimated to be as much as 1000 kg per engine. This clearly adds significantly to engine weight. A heat-exchange system this heavy requires further improvement and optimization before it can be incorporated into aero engines.

5. Intercoolers

Land based and marine propulsion gas-turbine developers have been more interested in utilizing recuperators. It is because intercoolers theoretically do not influence cycle efficiency but instead reduce the work required to compress air and hence increase the net work output while recuperators can contribute to an enhancement in the efficiency of the gas turbine cycle. In this regard, less literature is available relevant to intercoolers for gas turbines. Compared to recuperators, the operating conditions for intercoolers are mild; that is, a lower temperature capability and a lower pressure capability are required. Thus, there are fewer factors to consider in the development of an intercooler compared the development of a recuperator. This allows for a variety of manufacturing technologies and heat exchanger matrix configurations, including the use of heat exchanger types for recuperators, as mentioned in the previous section. Another thing to be mentioned is the density difference between high-pressure and low-pressure side gases of an intercooler and a recuperator. As the air for the intercooler entrance comes from the output of the intermediate compressor, the intercooler operating pressure must be lower than the recuperator operating pressure, which is at the same level as the high-pressure compressor (HPC) exit. The reduced density difference between the air on the high-pressure side and that on the low-pressure side can lead to less of a difference in the heat-transfer surface areas for both sides. This suggests that an intercooler can be designed without an extended surface, thus a primary surface type would be appropriate. If the intercooler uses water as a heat sink, however, an extended surface-type heat exchanger is more appropriate.

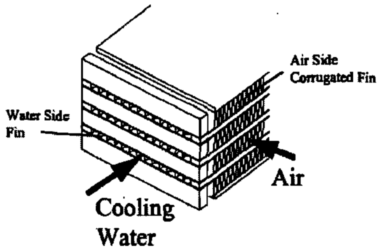

Fig. 11. PFHE intercooler by Toyo.

Fig. 11 shows a PFHE matrix configuration that was used as an intercooler in an ICR-MGT(24). Copper was used to fabricate this heat exchanger, as water is used to cool compressed air and copper has excellent corrosion-resistive properties. The same type of intercooler as this water-cooled PFHE was considered for a gas turbine with approximately a 17 MW power output.(25)

As WR21 is used for marine propulsion by the British Royal Navy, as well as the US and French navies, a compact system design is required. In order to meet this requirement, WR21 incorporates PFHX as an intercooler and utilizes seawater to cool the intermediately compressed air.(26) The GE LMS100 employs off-engine intercooling technology with the use of an external heat exchanger. Therefore, the type of intercooler heat exchanger can vary in accordance with the install location. MTU recently started work on the development of intercoolers for aero jet engines.(23) The intercooler under development will be a flat plate heat exchanger featuring a single passage, counter-flow arrangement.

6. New developments

Some types of modern nuclear power plants (NPPs) under development are based on the Brayton cycle. Nuclear power plant engineers have also been seeking novel heat exchangers as a recuperator.(27,28) The operating conditions of a recuperator in NPPs are similar to or harsher than those in gas turbines. For

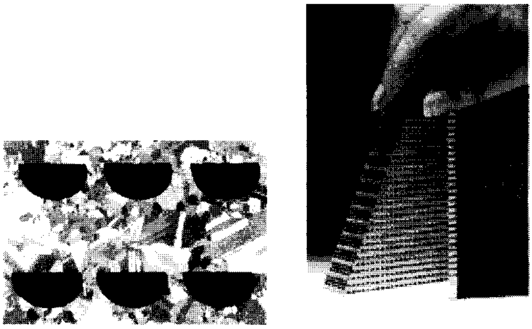

Fig. 12. PCHE by Heatric.

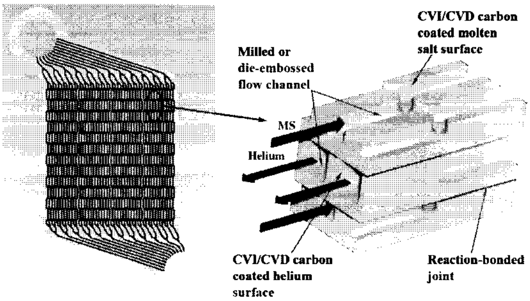

Fig. 13. Ceramic composite HX for hydrogen production.

instance, the temperature and pressure of this type of NPP can reach 950℃ and 7.2 MPa, respectively. A printed circuit heat exchanger (PCHE) developed by Heatric(27) is a plausible candidate. Fig. 12 shows this and it is a type of micro-channel heat exchanger. This heat exchanger is manufactured by chemically milling micro channels that are approximately 2mm in diameter into flat plates, and stacking and diffusion bonding plates together into a block.

Another interesting heat exchanger study is being carried out by a research team led by the University of Nevada at Las Vegas.(29) They are trying to utilize inexpensive chopped-carbon-fiber based ceramic composites to fabricate compact plate heat exchangers. Individual plates are formed by die-embossing flow channels using a mold. These plates are assembled and then undergo pyrolysis and infiltration process to make a monolithic heat exchanger module as shown in Fig. 13.

7. Conclusions

Gas-turbines play an important role in various power generation applications such as electric power generation, fluid pumping, ship propulsion, and aerojet engines. Most of gas-turbines incorporate various heat exchangers in order to secure robust operation. Recent environmental concerns push gas-turbine vendors to develop more efficient gas-turbines. As the benefits of intercooling and recuperating in a gas turbine have long been recognized, various heat exchangers have been developed for these applications. The heat exchanger matrix configurations and manufacturing methods depend on where they are applied. So the selection of heat exchangers for gas-turbine recuperators and intercoolers is influenced by many factors, such as the thermal performance, structural integrity, and weight. This review work shows that the recent advancement in heat exchanger technologies makes it possible to develop intercoolers and recuperators for large gas turbines as well as micro gas turbines.

Acknowledgement

This work was supported by the Korea Foundation for International Cooperation of Science & Technology(KICOS) through a grant provided by the Korean Ministry of Science & Technology(MOST) in 2007 (K20702000013- 07E0200-01310)

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