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Compact Heat Exchangers for Microturbines

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ABSTRACT

Within the distributed power generation market, the most economical solution today is to generate power through small gas turbine systems, arbitrarily categorized as microturbines (5-200 kW) and miniturbines (200-500 kW). The thermal efficiency of such microturbines without and with a recuperator is about 20 and 30% respectively, thus having a substantial performance improvement with a recuperator. The cost of the recuperator is about 25-30% of the total power plant cost, so there is an incentive to develop high performance recuperator at minimum cost. While the offset strip fin geometry is one of the highest performing surfaces, it is also expensive to manufacture due to brazing requirements. This favors the use of all prime surface heat exchangers with no brazing. Note that the compact heat exchanger surface design data are obtained experimentally in the current state-of-the art and many papers have been published. Hence, in this paper, our focus on recuperators will be on the design (various types of heat exchanger surfaces and novel designs), material/finished heat exchanger cost, performance, durability, packaging and other related issues. The discussion and coverage is primarily for metal heat exchangers since ceramic heat exchangers are still in the infant stage after the last 50 years of development associated with the gas turbine applications.

INTRODUCTION

At present, electric power is generated mainly in thermal power plants (using coal, oil or natural gas), hydro power plants or nuclear power plants. The power generation is generally in hundreds of megawatts. There is also a need for small power generation for remote areas, areas where grid power availability is low, emergency power, uninterrupted power and other specific cases. Currently, the most common mode is to generate small electric power by a Diesel engine; however, this is a costly power source compared to the grid power. With the decentralization of the power generation monopoly, more and more use of distributed power generation is taking place. The alternative way is to generate electricity using a gas turbine in a simple Brayton cycle. Gas turbine technology has advanced considerably over the last 60 years and power generation on a large scale (in 100s-1000s megawatts) is common. While gas turbine technology with a smaller power range (to produce power in 5-500 kW range) has been developed, it is very costly. Gas turbines producing power in the 5-200 kW range are referred to as microturbines and those in 200-500 kW range as miniturbines (McDonald, 2003). We define arbitrarily the ultra microturbines as having 5W–5 kW power range. We will now briefly summarize microturbine technology.

A "microturbine" or "micro gas turbine" implies a small compact gas turbine based power system. It includes: a turbocompressor (a radial turbine and centrifugal compressor on a single shaft), a combustion chamber, a generator, and a recuperator as an optional component. However, almost all microturbines require recuperators to achieve desirable system thermodynamic efficiency. At a pressure ratio of about 3-4, the efficiency of a microturbine is about 20% without a recuperator and about 30% with a recuperator, assuming a recuperator effectiveness of over 87%. Note that the typical efficiency of diesel and gasoline engines is 35-40% for the microturbine application range (about 5-300 kW). Even though the efficiency of a microturbine is low, it emits significantly lower levels of CO and NO_x, 100-200 ppmv for diesel and gasoline engines versus 25 ppmv for a micro-gas turbine.

Microturbine's optimum rotational speed is about 100,000 rpm for power rating below 10 kW and 93,500 rpm at 10 kW (Rodgers, 1974). The lowest rotational speed recommended for a 5 kW microturbine is 150,000 rpm which is not justifiable from an economic viewpoint. Note that due to small dimensions, the turbine blades are not air-cooled.

A typical open cycle, single shaft recuperated microturbine is estimated to have the lowest relative cost and weight and near maximum efficiency. The system % cost breakdown is of the order: Powerhead (turbocompressor) 25-30%, recuperator 25-30%,† electronics 25%, generator 5%, and packaging 5%. Additional options, such as closed and semi-closed cycles with precoolers and loop pressurization, will increase the relative costs beyond those shown above. Cost targets are: $600/kW or lower for a microturbine power plant, with a recuperator cost of 1.5 times the material cost (no more than about 25-30% of the microturbine cost). This requires very low cost manufacturing techniques for the recuperator. In order to meet this cost targets, the microturbine must be a simple system with a minimum number of simple components: single-stage radial compressor and turbine, direct-drive high-speed air-cooled generator, multi-fuel combustor, compact high-effectiveness recuperator, and a simple control system (Massardo et al., 2002). Packaging of the recuperator in the system should be compact. For example, it may be either a wrap-around recuperator around the turbogenerator for a very compact system (see Fig. 1) or a recuperator installed behind the rotating machinery that can be bypassed, if desired (see Fig. 2).

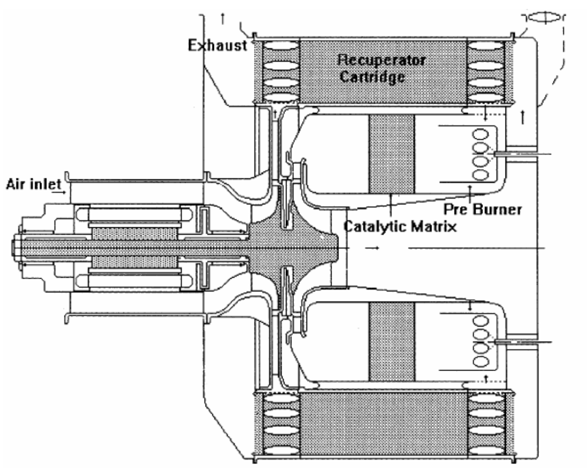


Fig. 1 Microturbine system with an annular wrap-around recuperator (McDonald, 2003).

If the simple Brayton cycle is modified to include a recuperator (which will transfer heat from the turbine exhaust to preheat compressed high pressure air before going to the combustion chamber), it will require less fuel to obtain the desired turbine inlet temperature of the compressed air. Also, the optimum pressure ratio for the compressor is reduced to typically 3-4 which improves the thermal efficiency of the cycle. Alternatively, a regenerator can also be used replacing a recuperator. A number of regenerative cycles are presented by McDonald and Wilson (1996). However, the durability and air-to-gas leakage problems are serious enough that the recuperator is not being considered after over 50 years of development. Very high performance brazed

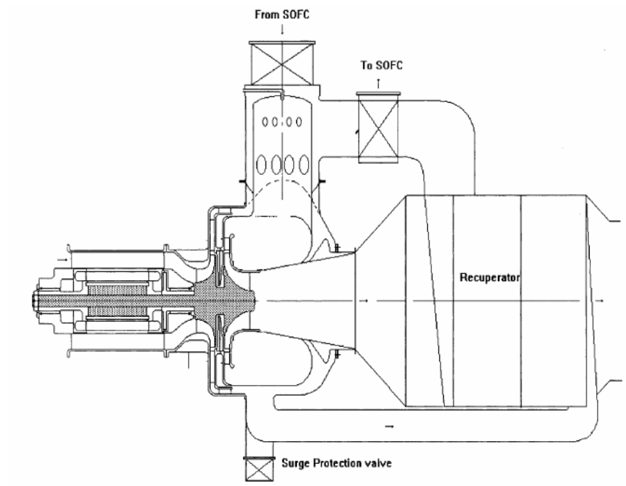


Fig. 2 Microturbine system with a rear-mounted recuperator (McDonald, 2003).

plate-fin type recuperators have been developed and are being used in large systems today.

With cost pressures, modern recuperator designs for microturbine systems use prime surfaces on both fluid sides with no brazing, just stacking. They are welded at the side edges to form air flow passages, to prevent leaks and mixing of the fluids. This allows high heat transfer performance with low pressure drop, an essential design requirement today. Since both fluids are gases (compressed air and turbine exhaust gas) in the heat exchanger, the design of inlet and outlet manifolds is challenging to ensure good flow distribution through the core on both fluid sides.

In this paper, starting with some historical developments, we will summarize microturbine developments and then compact heat exchanger (recuperator) developments for microturbines. After describing the current status, we will summarize the challenges and opportunities to make microturbines viable for distributed power generation.

MICROTRUBINE DEVELOPMENTS

Gas turbine development started just after the Second World War. Initially, the power generation plants used a simple cycle without the recuperator and with pressure ratio of up to about 7-8. Realizing a significant gain in gas turbine system performance with lower pressure ratios, the use of recuperators was considered from the beginning since the efficiency of non-recuperated gas turbine system is very poor (about 20% at a pressure ratio of 4:1). Since microturbines have been considered for distributed power generation, they have to compete with electrical power generated today in thermal or hydropower plants which have power generation costs about $1000/kW or lower. This requires the cost targets lower than $1000/kW for microturbine power plant. This represents a significant challenge for the new technology to enter in the market. There is only a

† The useful power generated increases with a recuperator by about 50% with 25-30% cost increase in the microturbine power plant.

limited market at present for military applications and commercial applications where the cost of electric power is not so critical compared to the overall cost of getting the required power, such as: remote areas having no grid lines or no cost effective way of connecting to the grid line, a need for clean uninterrupted stationary power, and a requirement for portable power requirement.

Microturbine Performance

The general operating conditions for a micro-turbine are (1) a turbine inlet temperature of 800-1000°C, and (2) compressor and turbine efficiencies 82 and 83.5% respectively (Kesseli et al., 2003). Detailed operating conditions for a typical 50 kW first generation stand-alone microturbine system based on proven technology and a microturbine coupled with a fuel cell system are provided by (Massardo et al., 2002). These machines have radial flows (with smaller blade heights) and hence have lower efficiency and lower performance than large machines with axial flows (long blades). It should be emphasized that if the pressure ratio is high, let us say greater than 8-10, the compressor discharge temperature will be high and turbine exit temperature will be low requiring no recuperator.

Starting with the current thermal efficiency of about 30% for recuperated microturbines, the increase in efficiency and reduction in specific fuel consumption of microturbines is depicted in Fig. 3. As one can find, the long term projection for the thermal efficiency of a microturbine is about 50% using a ceramic recuperator with effectiveness of 95% and a turbine inlet temperature of about 1750°C.

Microturbine Technology Status

Microturbine development started in 1990. Here, we will briefly present the turbomachinery development.

The major manufacturers of microturbines in 2001 were: Capstone (30 and 60 kW), Elliot (100 kW CHP system), Ingersol-Rand (70 and 250 kW) and Bowman (80 kW) in USA; Nissan (2.6 kW) in Japan; Turbec (100 kW) in Europe.

Honeywell fuel cell turbocompressor as shown in Fig. 4 is light weight (<15 kg), efficient (η_c = 75% and η_t = 80%), reliable (since it has only one moving part), has zero maintenance requirements, is capable of high temperatures, and is in modular form. This turbocompressor is further being developed under a DOE contract. This turbocompressor will have the following performance at a 2.5:1 pressure ratio and 100 g/s airflow: compressor efficiency of 72%, expander/turbine efficiency of 80%, 6 kW with turbine assist and up to 15 kW during startup/transient. By 2010, this turbocompressor will be further refined so that compressor may have 80% efficiency and the turbine will have 85% efficiency. The projected cost will be $400/unit for 100,000 units/year production.

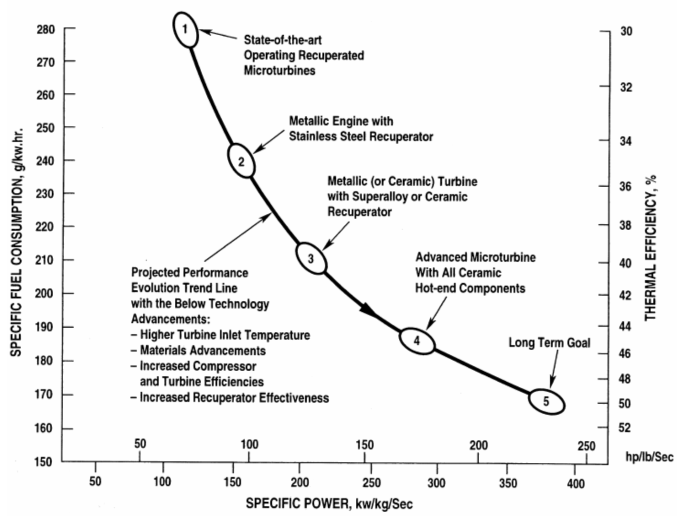


Fig. 3 Microturbine performance projection (Massardo et al., 2002).

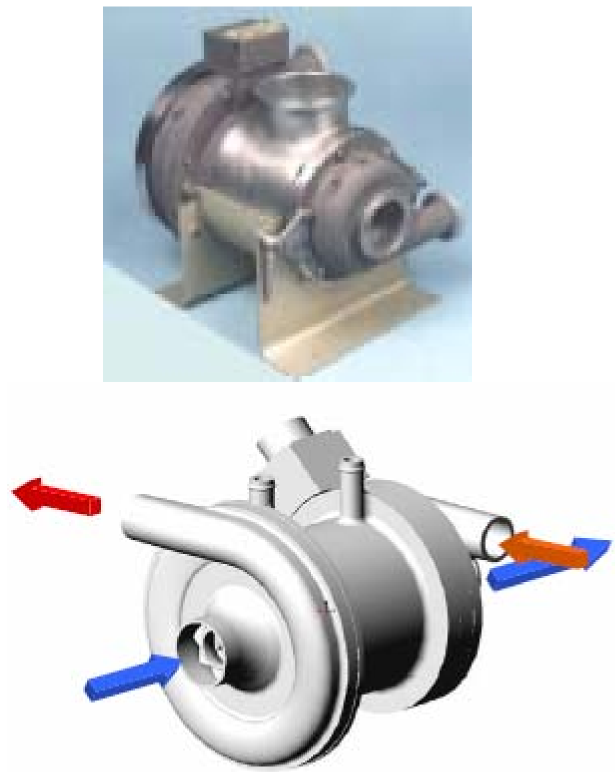


Fig. 4 Honeywell turbocompressor development from the first generation to the latest (Ordonez et al., 2004).

Traverso et al. (2003) provided a brief overview of microturbine control systems and the transient behavior of two advanced cycles: an externally fired micro gas turbine cycle and a solar closed Brayton cycle.

RECUPERATOR REQUIREMENTS FOR MICROTURBINES

Since the cost of a recuperator is high (about 25-30% of the recuperated gas turbine system (McDonald, 2000a), the recuperator must have high performance. The desired performance requirements for microturbine recuperators are summarized in Table 1 by McDonald (2000b), and Muley and Sundén (2003) as follows:

- High exchanger effectiveness ε ($\geq$ 90%). This means a counterflow arrangement) and low total pressure drop ($\Delta p/p$ < 5%) with the core pressure drop of about 3% and the remaining in manifolds and piping.
- High operating temperatures and fluid pressures (about 675°C and 4 bar), and capable of withstanding steep temperature transients during startup and shutdowns.
- Desired 40,000 hour operation life without any maintenance for stationary power generation applications. This would translate into good thermal shock, corrosion, oxidation and creep resistance and low thermal expansion.
- Compact (i.e., small hydraulic diameter surfaces) and lightweight matrix with integral manifolds (having low pressure drop and uniform flow distribution), and mass producible low cost design.

The aforementioned requirements translate into a thin foil primary surface recuperator (same surface on both fluid sides) with stamping, folding and welding side edges by an automated operation to form flow passages on the air side. There is no brazing.

For a low cost recuperator for microturbines, McDonald (2000) summarizes the following important parameters for recuperator design: use only primary surfaces, minimum number of parts, almost 100% utilization of material, welded construction, automated high volume manufacturing process, compact light-weight heat exchanger, matrix fabricatable in annular or box type construction, and ease of installation, removal and replacement of the matrix. The most important of all criteria is the low cost.

RECUPERATOR DEVELOPMENT

Following are the major steps in the design and development of a gas-to-gas recuperator (modified from Ayres and Beddome, 2001):

- Find out approximate core size using prior empirical data and finite difference tools.
- Manufacture heat transfer surface and test to determine j and f versus Re design data.
- Determine core size and tool sample plates for manufacturing development and test cores.
- Analyze flow and temperature in the core using CFD to predict flow and temperature distribution, as well as verify performance.
- Compute thermal stresses using transient temperature distribution models input into finite

Table 1. Microturbine recuperator requirements

Major design criteria	• Low heat exchanger cost • Meet demanding microturbine performance and economic goals • High recuperator reliability
Perform-ance	• High recuperator effectiveness (> 90%) • Low pressure loss (< 5%) • Good part load performance
Surface geometry	• Prime surface geometry (no secondary surface inefficiency) • High surface compactness • Superior thermal-hydraulic characteristics
Fabrica-tion	• Minimum number of matrix parts • Continuous/automated fabrication process • Welded sealing (eliminate need for furnace brazing) • Adaptable to high volume production methods • Utilize heat exchanger industry experience (e.g., automobile radiators)
Type of construc-tion	• Compact and light weight matrix • Integral manifolds/headers • Matrix envelope flexibility (annular or platular)
Cost	• No basic material wastage (zero scrap) • Minimum (or zero) labor effort • Standardization • Materials selection for particular duty • Unit cost goal not to exceed 1.5 times material cost
Integrity	• Resistant to thermal cycling • Remain leak tight for engine life • Life goal of 50,000 hours for microturbine generator sets
Installa-tion	• Gas flow path compatibility with turbo-machinery • Compact and light weight overall assembly • Eliminate inter-connecting ducts • Eliminate need for thermal expansion devices
Mainte-nance	• Ease of recuperator removal/ replacement • Plug-in matrix cartridge (analogous to oil filter element) • Ease of leak detection testing • Ease of weld repair
Perform-ance growth capability	• Adaptable to future higher temperature microturbine variants • Materials selection flexibility • Adaptable to bi-metallic construction • Retrofit capability with advanced heat exchanger concepts
Near-term goal	• High volume production of cost-effective metallic recuperator with demonstrated performance and structural integrity for emerging family of microturbines
Long-term goal	• Development of a ceramic recuperator to facilitate the full performance potential of microturbines to be realized (i.e.. 45±50% efficiency)

element analysis program. If thermal stresses are not acceptable, modify appropriately the heat transfer surface design.

- Build cores, instrument and test to verify thermal models.
- Refine the design to mitigate risks brought to light by the analysis and test results.

RECUPERATOR STATE-OF-THE ART TECHNOLOGY

In this section, we will summarize various heat transfer surfaces contemplated and used over the years with gas turbines with a primary focus on microturbine applications. However, hundreds of recuperator heat transfer surface geometries have been investigated by the researchers over last 60 years or so for a variety of applications.† In order to achieve high recuperator effectivenesses, the heat exchanger must be of counterflow type with design effectiveness at the operating point above about 87% to achieve the microturbine system efficiency of at least 30%.‡ The desired cost of a fully fabricated and functional recuperator should be no more than about 1.5 times the metal cost of the recuperator (McDonald, 2000). However, today the cost in small production volume is up to 5-10 times the material cost.

Two types of recuperators are being considered: annular wrap-around recuperator (see Fig. 1) and rear-mounted cube type recuperator (see Fig. 2). The advantages of the first type are: a compact design with good aerodynamic gas flow path having low pressure drop, a lower acoustic signature, a built-in rotor burst shield, and no need for external ducts and thermal expansion devices. The advantages of cube-shaped recuperator are: simplicity for hot gas bypass for cogeneration, an external combustor for a variety of dirty fuels, and potential coupling of a recuperated microturbine and a high temperature solid oxide fuel cell (McDonald, 2003).

Some of the materials used for the recuperator are: 300 series stainless steel (AISI 347 SS) for temperatures below about 675°C, Inconel 625, Inconel 803, Haynes 120, Haynes 214 and PM2000 materials up to about 900°C. For a 50 kW microturbine, the recuperator would weigh about 40 kg and the thin foil stainless steel would cost about $12/kg. Thus the recuperator material cost would be about $500 (McDonald, 2000).

† Design data for over 100 early surfaces up to 1967 have been summarized by Kays and London (1998). Recent correlations for heat transfer and flow friction data are summarized by Shah and Sekulić (2003).

‡ The influence of longitudinal heat conduction on the recuperator effectiveness becomes more important and significant with increasing exchanger effectiveness above about 85%, and must be taken into account to obtain the desired high performance (Shah and Sekulić, 2003).

Plate-fin recuperator technology and manufacturing processes are known and there is good design flexibility. There are some important limitations for plate-fin designs: high capital cost, long braze cycle, potential for high repair rate, limited material flexibility, complicated assembly and difficult automated manufacturing. Thus the current emphasis is on the development of a recuperator using primary surface only with the following attributes (Ayres and Beddome, 2001):

- Basic core construction consists of a Laser welded stack of stamped plates (one or two parts).
- Simple construction leads to highly robust design.
- Fully automated Laser welding process is possible to seal side edges and form flow passages on one fluid side. Laser welding eliminates high cost of nickel braze materials that are traditionally used in high temperature heat exchangers.

Plate Type Primary Surface Recuperators

The noncircular plate type primary surfaces have been used by the heat exchanger industry long before its use in gas turbine applications was envisioned. The surface area density (heat transfer surface area divided by the volume occupied by the surface) of early technologies was not high. Hence, there was a need to use fins on the gas side in the case where other fluid had a high heat transfer coefficient (so that the exchanger becomes compact for space considerations), and there was no cost pressure. For this reason, the development of extended surfaces was accelerated by developing plate-fin surfaces after the invention/introduction of salt-dip brazing technology in late 1930s. In order to get better control of the brazing process, reduce cleanup of the finished product, and eliminate environmental concerns due to fumes and water pollution resulting from cleanup after brazing, salt dip brazing was replaced by vacuum brazing technology in early 1980s as soon as the latter became commercially available. The neutral environment (NOKOLOCK) atmospheric brazing technique introduced in mid 1980s has replaced some vacuum brazing (such as in automotive aluminum exchangers) due to lower brazing cost.

In a gas-to-gas recuperator as in the microturbine application, the heat transfer coefficients are not significantly different and the use of all primary surface heat exchanger will provide a balanced heat exchanger from the optimum heat transfer surface area point of view. This is not the case for a liquid-to-gas heat exchanger in which case the heat transfer coefficient on the liquid side is probably 3 to 10 times higher than that for the air side; this necessitates the use of fins on the gas side for a balanced heat exchanger. The use of all primary surface recuperator for microturbine applications is envisioned from the cost reduction point of view since the manufacturing can be automated. With improved and relatively less expensive well-established manufacturing technology, thin metal foils (i.e., a stack of formed plates) can be formed into any desired shape as recuperator surface,† and the recuperator core can be made in any shape and size. Subsequent headering and manifolding result in a full recuperator. No brazing is required and hence there is no need of braze-alloyed sheets. Only welding is required at the edges of a pair of plates to form the leek-free hot and cold gas flow paths. A recuperator can be made of two metals with the expensive high temperature alloy in the high temperature zone and stainless steel or other less expensive metals in low temperature zone of the recuperator (McDonald, 2003). While most highly compact extended surfaces used in automotive and other applications have fin efficiency of 90% and higher, there is some advantage of all primary surfaces having fin efficiency of 100%, i.e., the surfaces are fully effective from heat transfer point of view.

Solar Turbines, Caterpillar and Capstone Turbine Corporation companies of USA have manufactured several thousand annular recuperators, as shown in Fig. 5 (Treece et al., 2002) with individual cells having an involute form. The recuperator is about 45.7 cm in diameter, has 169 air cells, and each air cell is fabricated by welding individual fin-folded 347 stainless steel having 0.10 mm initial thickness. These units are for 30 and 60 kW microturbines, fully welded to seal sides and form flow passages, and have undergone extensive testing and thermal cycling thus proving the durability and reliability. The control system of microturbine limited the turbine speed to 60,000 rpm. At 45,000 rpm, the maximum inlet temperature to the recuperator is 843°C.

Rekuperator Svenska AB of Sweden (Lagerström and Xie, 2002) has developed a primary surface recuperator having thin corrugated austenitic stainless steel plates; two such plates are laser welded around the perimeter of two opposite sides to make a flow passage for air flow. Such plate assembly has two crossflow zones in the ends with a counterflow section in between as shown in Fig. 6. The triangular crossflow sections provide uniform flow leading to the counterflow section. The corrugation height is lower in the crossflow zone for easy airflow entry/exit through the gap produced in the airflow passage. The air cells are stacked and connected to make the recuperator core. A finished recuperator with the core, manifolds, end beams and tie bars is shown in Fig. 6a, and a typical corrugated plate is shown in Fig. 6b. The minimum design effectiveness is 89% and the maximum total $\Delta p/p$ is 4.5%. The manufacturing cost is minimized by stamping technology for air cells and robotized high speed laser welding for assembling the air cells. A 100 kW unit has been designed and developed for combined electricity and cogeneration.

Muley and Sundén (2003) describe a prime surface counterflow (with crossflow headers) recuperator developed by Honeywell Corporation. The

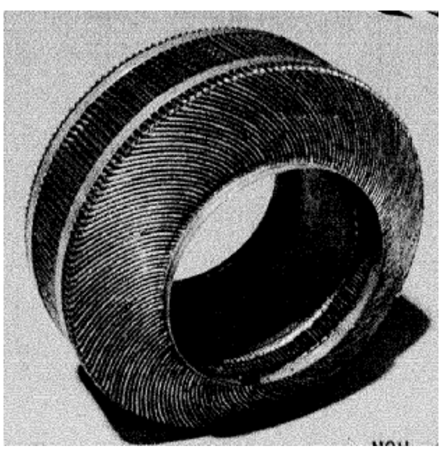
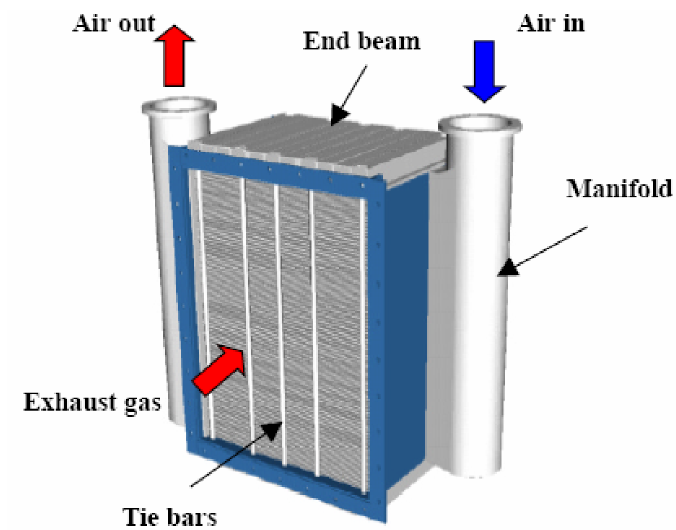
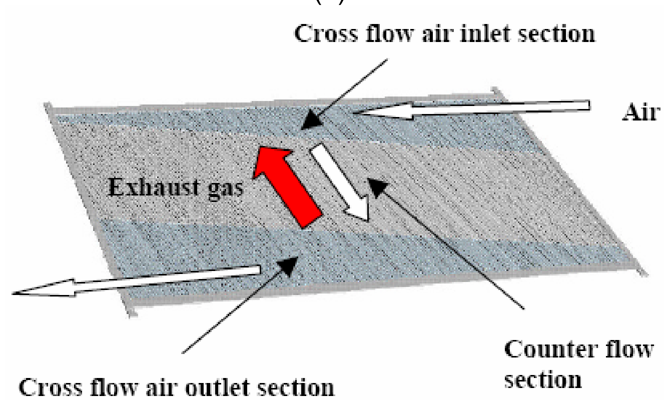


Fig. 5 Annular primary surface stainless steel recuperator from Solar Turbines, Inc. (Treece et al., 2002).



(a)

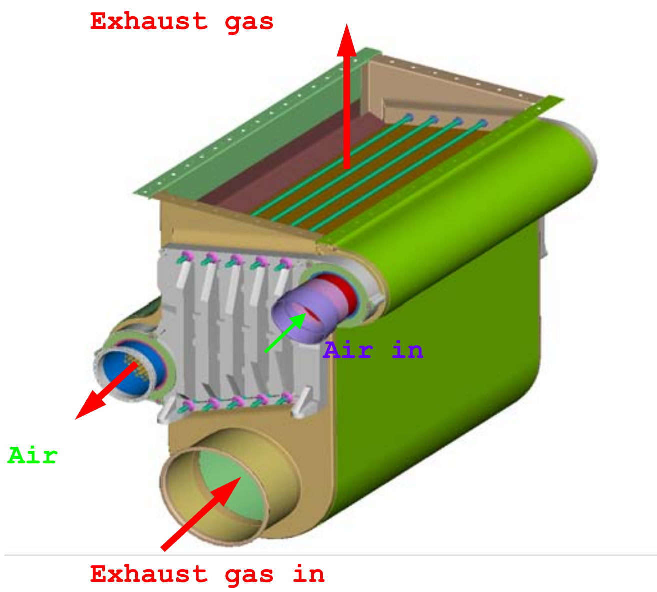


(b)

Fig. 6 (a) Primary surface recuperator, and (b) a typical air passage geometry (Lagerström and Xie, 2002).

†The recuperator core is made by folding the thin foil, pressing and trimming the individual sheets, welding two sheets to generate basic flow passage on one fluid side, and pressure testing for a leak free cell.

construction features are shown in Fig. 7. The plates have corrugations in heat transfer region, and in the inlet and outlet manifolds, all made in a single die operation. These plates are welded at the periphery to form alternate gas and air flow passages. Such plates are stacked, with thick end plates at both ends of the stack, and tied together with tie rods.



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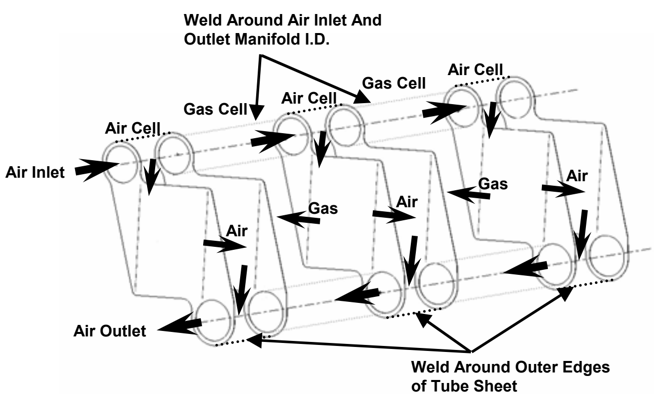
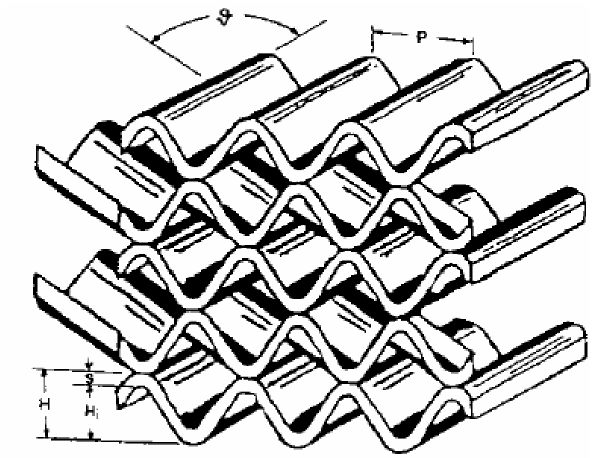


(b)

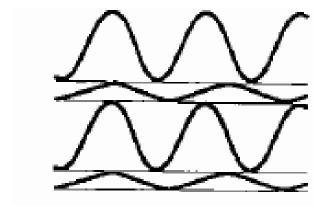
Fig. 7 (a) Honeywell prime surface recuperator, and (b) details of the core construction (Shah and Muley, 2002).

The other prime surface recuperators developed are presented by Proeschel (2002) and Antoine and Prieels (2002). Proeschel describes an annular flow concentric tube counterflow recuperator using a novel manufacturing method. Antoine and Prieels detailed a spiral (coiled) stainless steel recuperator designed for reliability, compactness and low cost.

Many innovations have taken place in the recent years to arrive at high performance cost effective prime surfaces for the microturbine applications. McDonald (2000b) briefly describes the stamped and



(a)



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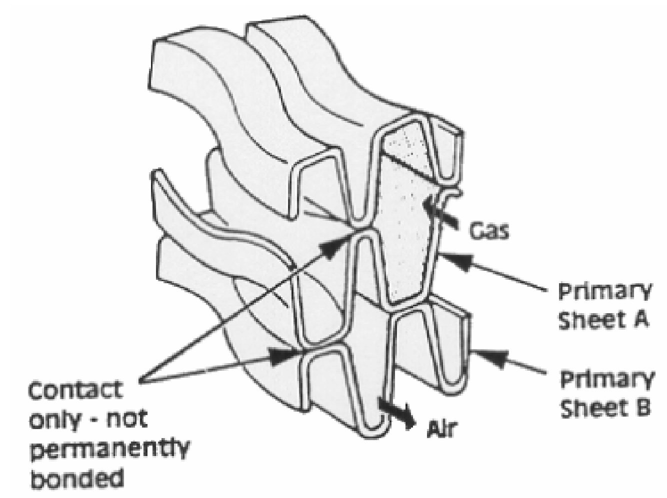

(c)

Fig. 8 Plate-type prime surface recuperator surfaces: (a) Cross corrugated (CC) surface, (b)Corrugated Undulated (CU) surface, and (c) Cross wavy surface (Utriainen and Sundén, 2001).

folded heat transfer surface, as shown in Fig. 8a, and referred to as herringbone corrugations or cross-corrugated (CC) surface. The other recent surfaces are cross-undulated (CU) surface and cross-wavy (CW) surface (see Fig. 8). Historical developments of these surfaces have also been summarized by Utriainen and Sundén (2001). Further details of CC, CU and CW surfaces are as follows:

- The construction of the cross corrugated (CC) surface is simple. It is pressed and stamped or folded to the right corrugation pattern. To make a two-fluid heat exchanger, it is welded at the edges. This surface is used in the process industry. For this cross corrugated surface, the higher the corrugation pitch to height ratio P/H, the smaller is the pressure drop and Nusselt number.
- The corrugated undulated (CU) surface was used as the heat transfer surface in a compact rotary regenerator developed for a vehicular gas turbine engine power plant. In this application, a single fluid (either hot gas or cold air) is passing through a part of the matrix and the other fluid in the rest of the matrix flowing in the counterflow direction. However, for the gas turbine application, it is a two-fluid exchanger with cold air flowing through small passages and the hot gas flowing through large passages in counterflow direction. The construction of the CU surface is the similar to that for the CC surface, except there are two different types of plates to be fabricated resulting in higher cost. The passage size (height) can be selected such that the high pressure air has a smaller size passage so that hA† on each fluid side is approximately the same thus making an optimum performance heat exchanger from the total surface area requirement.
- The cross wavy (CW) surface has approximately rectangular (or trapezoidal) flow passages with waviness induced along the flow direction, and the upper and lower half has the waviness offset in the opposite direction from the line of symmetry. This surface is difficult to make by pressing or stamping processes due to the high height and small pitch; it is instead made by a folding process. However, the CW surface having a short wave length is difficult to fold due to potential cracking of the surface.

Geometrical information of some of these surfaces is presented in Table 2 and heat transfer and flow friction characteristics are presented in Table 3 (Utriainen and Sundén, 2001). The Nu and fRe data for these surfaces are obtained experimentally for the CC surface and numerically for the CU and CW surfaces (Utriainen and Sundén, 2001). Utriainen and Sundén recommend the CC surface of having the best potential for use in compact recuperators of the future.

Tubular Primary Surface Recuperators

A tubular primary surface has the advantage of containing high pressure fluid within the tube with a minimum wall thickness compared to any other noncircular all prime surface geometry. In this regard, highly compact tubular recuperators were developed in early 1990s with the tube inside diameters of 1 and 0.3 mm with all automated manufacturing technology developed. But due to the high cost, commercialization did not take place. The performance disadvantages of a circular tube core are: it has a lower surface area for a given flow area compared to rectangular cross sectional geometry; it has a lower heat transfer coefficient compared to rectangular cross sectional geometry; it has higher pressure drop on the tube outside fluid side due to parasitic form drag associated with a circular tube. Hence, the current focus is to use elliptical tubes in the recuperator as shown in Fig. 9 to obviate the circular tube performance disadvantages. This recuperator has shown high structural integrity in addition to the performance (McDonald, 2003).

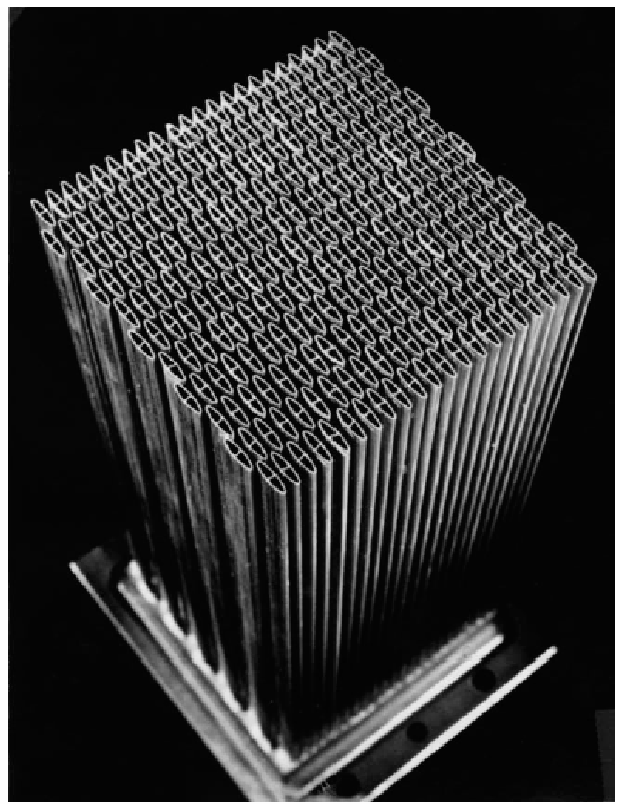

Fig. 9 Elliptical tube recuperator (McDonald, 2003).

Extended Surface Recuperators

Brazed plate-fin recuperators have been used by industry for over 50 years for a variety of applications. The most efficient fin surface used is the offset strip-fin geometry. From the low cost viewpoint, corrugated plain fins are used. For higher performance and still lower cost than that for the offset strip-fin geometry, multilouver (or simply now referred to as louver) fins have been used in recuperators. Louver fins are common for all automotive heat exchangers today.

Ingersoll-Rand Energy Systems (Kesseli et al., 2003) has developed a plate-fin recuperator as shown in Fig. 10. The construction is very similar to the one shown in Fig. 7 except that the black region shown in the core has fins on flat sheets and the rest of the gray

† h is the heat transfer coefficient and A is the heat transfer surface area on same fluid side for which value of h is mentioned.

Table 2. Geometrical data of all surfaces

Type	Surface	Pitch P [mm]	Int. Height Hi [mm]	Length l_{uc} [mm]	Amplitude of Waviness Aw [mm]	C [m^2/m^3]	θ [degrees]	D_h [mm]
CC	CC-45	3.48	0.87	4.54	-	1299	45	1.54
CC	CC-60	3.48	0.87	3.48	-	1299	60	1.54
CC	CC-75	3.48	0.87	2.85	-	1299	75	1.54
CW	CW2-z3	1.38	2.28	2.98	0.99	1717	-	1.54
CW	CW2-z5	1.38	2.28	4.96	0.99	1422	-	1.54
CW	CW3-z3	1.38	2.28	2.98	0.79	1496	-	1.54
CW	CW3-z8	1.38	2.28	7.94	0.79	1343	-	1.54
CU	UCS-30	2.24, 3.17	1.30, 0.79	6.33	-	1299	30	1.54
CU	UP2-30	2.78, 2.15	1.61, 0.45	4.30	-	1299	30	1.54
CU	US-50	2.74, 2.66	1.59, 0.44	3.47	-	1299	50	1.54
Plate-fin	strip-fin	1.63	1.62	3.20	-	1192	-	1.54

Table 3. Coefficients of correlation equations in the form [Nu, f*Re] = $C_1 + C_2$*Re

	Nu		fRe	
Surface	C_1	C_2	C_1	C_2
CC-45	2.9241	0.7655E-02	21.3186	0.2948E-01
CC-60	3.8988	0.1021E-01	42.4535	0.5928E-01
CC-75	6.1107	0.1478E-01	85.6395	0.1362
CW2-z3	2.4101	0.2315E-01	61.8672	0.4427
CW2-z5	1.0441	0.1570E-01	35.1707	0.1168
CW3-z3	-0.5256	0.2309E-01	51.7276	0.2524
CW3-z8	1.8194	0.3878E-02	26.1720	0.3131E-01
UCS-30	6.7538	0.1155E-02	37.0463	0.1392E-01
UP2-30	3.07377	0.2929E-02	16.2233	0.9531E-02
US-50	2.8500	0.5130E-02	17.7878	0.2040E-01

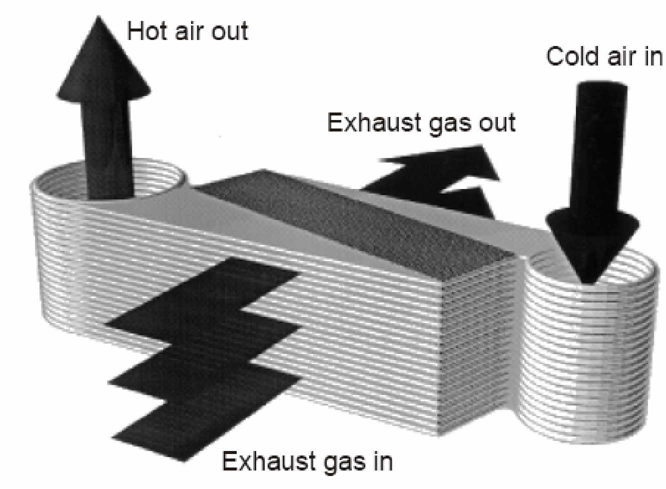

Fig. 10 Recuperator sketch showing flow paths. Manifolds for cold air entering and hot air leaving the recuperator are created by welded circular flanges (Kesseli et al., 2003).

sheet has corrugated pattern and represents a crossflow zone for entering/exiting air/gas flows. This design is very durable with negligible fatigue. The manufacturing details are summarized by Kesseli et al. (2003). The assembled core may contain 1 to 200 unit cells. Kesseli et al. have also provided performance data, analysis and cost information. They have shown that the optimum pressure ratio for maximum recuperated turbine shaft thermal efficiency is dependent on the turbine inlet temperature. For microturbines, this optimum ratio is about 4:1 at turbine inlet temperature of 800-900°C. The recuperator core cost reduces drastically for increasing specific power kW/kg. The cost of AISI 347 and Inconel 625 was 7.00 $/kg and 24.30 $/kg respectively in 2002. For recuperator gas inlet temperature above 700°C, there is a step function change in the recuperator core cost due to the use of Inconel 625 in addition to slower processing time and low thermal conductivity of Inconel 625. Finally, the analysis of Kesseli et al. shows that the recuperator with 90% effectiveness costs about 50% more than the recuperator with 85% effectiveness with 4% pressure drop in both cases.

Recuperator Material Development

Pint et al. (2002) investigated the effect of water vapor in exhaust gas on the oxidation resistance of a recuperator made of 321 stainless steel Inconel 625, Haynes 214 and PM2000 materials. 321 SS was found to have relatively low oxidation resistance at 700°C. High chromium and high alumina content alloys had less susceptibility to water vapor effect.

Lara-Curzio et al. (2002) developed a test facility to screen and evaluate potential recuperator materials up to 843°C for microturbine application. The test facility included a modified 60 kW Capstone microturbine to subject test specimens in accelerated testing for stress, environment and temperature experienced by a recuperator in microturbine applications.

Recuperator Specific Size and Cost

In order for microturbines to be economically viable, the recuperator must be cost effective and compact for applications that require compact packaging. One such application is hybrid vehicle. A hybrid engine with a microturbine would generate electricity at the maximum efficiency and the hybrid vehicle would run this on electricity. For an automotive application with an engine power rating of 65-100 kW and cost $25/kW, the recuperator should be manufactured for about $150. Such an exchanger should be operating at high temperatures, be built using low-cost manufacturing methods and be easy to replace or maintain (McDonald and Wilson, 1996).

REGENERATORS

After presenting historical developments of recuperators and regenerators, Wilson (2003) conducted the analysis of the effect of regenerator effectiveness on gas turbine cycle efficiency and optimum pressure ratio as shown in Fig.11. He discussed key issues for heat exchanger design and pressure drop balance (hot gas versus cold air side).

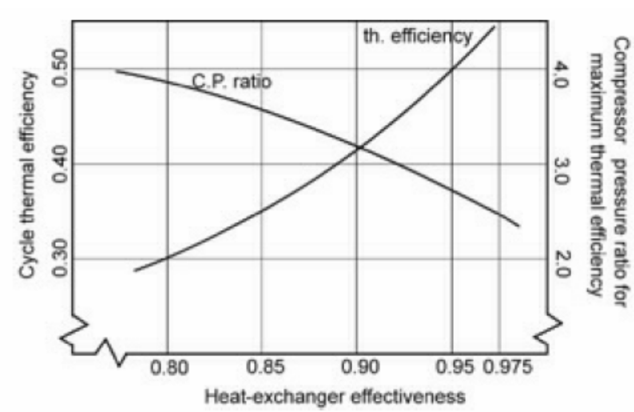

Fig. 11 The gas turbine cycle thermal efficiency and optimum pressure ratio as a function of the heat exchanger effectiveness (Wilson, 2003).

Finally, he presented a novel concept of discontinuously moving core of a regenerator to significantly reduce the leakage from high pressure cold air to low pressure hot gas. Wilson concluded that a gas turbine cycle with a high effectiveness regenerator could reach up to 50% electric efficiency for microturbines of 300 kW and over.

CHALLENGES AND OPPORTUNITIES FOR RECUPERATOR DEVELOPMENTS

In order to realize the cost goals of a recuperator of about 1.5 times the material cost, there are a number of short and long term challenges briefly summarized as follows.

Short Term Challenges

The following are some short term challenges:

- Conduct the cost optimization of the recuperator for a specific application using primary surface geometry by varying the geometrical parameters, as well as some operating variables.
- Develop the whole manufacturing process (stamping, folding, compacting and welding) from the sheet metal to annular/cube form recuperator for minimum cost, including the pressure/leak test of the seal integrity of the welded ends.
- Conduct performance testing for heat transfer and pressure drop, thermal cycle testing for structural integrity, and vibration testing for durability.
- The development of high temperature materials with reasonable cost is essential for improving the regenerator and microturbine performance with lower cost.
- The final design must operate for 40,000 hours without any maintenance.
- Develop a recuperator using one of the highest performing surfaces, a cross-corrugated surface shown in Fig. 8a.
- The cost target challenge for the recuperator is about $10/kW and the recuperated microturbine efficiency of 30% (McDonald, 2000).

Long Term Challenges

The long term goals will be continuous improvement and cost reduction; increase in performance in the same packaging volume; increase in turbine inlet temperature. However, the last goal will have a significant negative impact on the cost since superalloys must be employed if the inlet temperature to the recuperator increases over 700°C. The cost of using these materials is 3-5 times higher than the conventional materials such as stainless steel. The cost of superalloy could be reduced if bimetal sheets are used carefully in a counterflow recuperator; part of the core with high temperature superalloy remains in the hot zone (high temperature region) and the remaining core with stainless steel material remains in the low temperature region. The details of this concept were suggested by McDonald (2000). A very long term goal would be to increase the turbine inlet temperature over 1225°C, and use ceramic recuperators to withstand recuperator inlet temperatures of over 900°C.

CONCLUDING REMARKS

A comprehensive review is made of compact heat exchangers used or proposed in microturbines. Starting with a brief description of microturbine developments, detailed information is provided for recuperators. This includes recuperator requirements, developments and the state-of-the-art technology. The last item is focused with the details on plate type primary surface, tubular and extended surface recuperators, recuperator material developments, and recuperator specific size and cost. Also summarized very briefly are the developments in regenerators. From the cost, performance and durability points of view, the prime surface plate type recuperators have the most potential in the microturbine applications.

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