Compact Heat Exchangers for Microturbines

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ABSTRACT

With 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 is about 20% or less if no recuperator is used in the system. Using a recuperator (regenerator can also be considered but has a number of problems) operating at 87% effectiveness, the efficiency of the gas turbine system increases to about 30%, a substantial performance improvement. However, cost of the recuperator is about 25 – 30% of the total power plant. This means that the heat exchanger (recuperator) must be designed to get high performance with minimum cost. While the offset strip fin geometry is one of the highest performing surface it is also quite expensive to manufacture. This necessitates the use of all prime surface heat exchangers with no brazing. In this paper, after providing the necessary concise information on microturbines, the discussion is presented on various types of heat exchanger surfaces and novel designs considered for the cost effective heat exchangers and packaging in the system. For hot fluid inlet temperature of less than about 675°C, stainless steel material can be used for the heat exchanger, which has reasonable cost. However, for higher inlet temperatures in heat exchangers associated with higher turbine inlet temperatures, superalloys are essential which increases the material cost of the exchanger alone by a factor of 4 to 5. The design, material/finished heat exchanger cost, performance, durability, and other related issues of compact heat exchangers for microturbines are covered in this paper. The discussion and coverage is primarily for metal heat exchangers since the ceramic heat exchangers are in infant stage after last 50 years of development associated with the gas turbine applications.

1.0 INTRODUCTION

At present, the electric power is generated mainly in a thermal power plant (using coal, oil or natural gas), hydro power plant or a nuclear power plant. The power generation is generally in Megawatts. There is a need for small power generation for remote area, not enough grid power availability, emergency power, uninterrupted power requirement and other reasons. With the decontrol on centralized power generation monopoly, more and more use of distributed power generation is taking place. The common mode is to generate the power by a Diesel engine. This is a costly power generation. The alternative way is to generate electricity using a gas turbine in a simple Brayton cycle. The gas turbine technology has advanced considerably over the last 60 years and the power generation on a large scale (in Megawatts) is common particularly in hydro and thermal power plants. While the gas turbine technology with smaller power range (to produce power in 5 – 500 kW range) has been developed, it is very costly. The gas

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turbines developing power in the range 5 – 200 kW range are referred to as microturbines[†] and those in 200 – 500 kW range as miniturbines (McDonald, 2003). We will now briefly summarize the microturbine technology.

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 compressed air and also the optimum pressure ratio (either for compressor or turbine) is reduced to typically 3 – 4. This 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. The regenerator development also started after the Second World War. Very high performance brazed plate-fin type recuperators have been developed and are being used in large systems today. With cost pressures, the modern recuperator designs for microturbine systems use prime surfaces on both fluid sides with no brazing, just stacking, and welded at the side edges to form air flow passage, to prevent the 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.

When using a recuperator in a microturbine, the recuperator cost is about 25 – 30% of the microturbine system. When a significant cost reduction is necessary, the brazed plate-fin type costly recuperator is not acceptable. The alternative is to use a high performance prime surface recuperator without any brazing. This avoids the costly fin manufacturing and brazing thus reducing the cost of the recuperator without performance reduction.

In this paper, starting with some historical developments, we will summarize the 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 viable the microturbines for distributed power generation.

2.0 MICROTRUBINE DEVELOPMENTS

Gas turbine development started just after the Second World war, first a simple cycle without the recuperator and with the 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% or so at a pressure ratio of 4:1. Since a microturbine is considered for distributed power generation, it has to compete with the electrical power generated today in thermal or hydropower plants which cost about $1000/kW or lower. This requires the cost targets of $ 600/kW or lower for microturbine power plant. This represents a significant challenge for the new technology to enter in the market. There is only a 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: in remote area where there is no grid line exist or there is no cost effective way of connecting to the grid line, a need for clean uninterrupted stationary power, portable power requirement, etc.

[†] A “microturbine” implies a small compact gas turbine based power system and includes a turbocompressor (a turbine and compressor on a single shaft), a combustion chamber and a generator, with recuperator as an optional component. However, almost all microturbines require recuperators to achieve desirable system thermodynamic efficiency.

2.1 Major Features of the Microturbines

The following are the major features of microturbines in order to make a cost effective system:

- It 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 recuperator in the system should be compact, either a wrap-around recuperator around the turbogenerator for a very compact system (see Fig. 1) or a recuperator installed behind the rotating machinery (see Fig. 2) to either bypass the recuperator if desired or the heat recovery from the exhaust of the recuperator downstream.

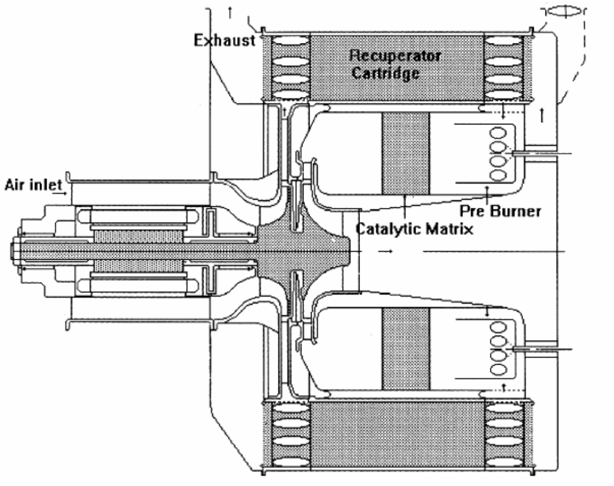

Figure 1: Microturbine System with an Annular Wrap-Around Recuperator (McDonald, 2003).

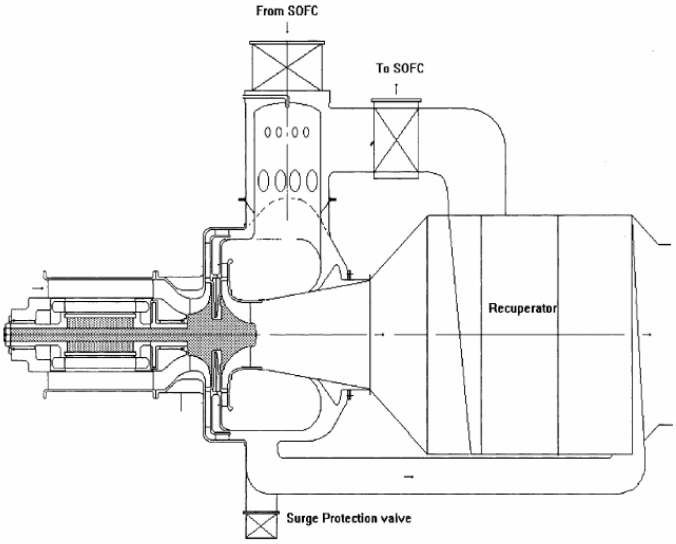

Figure 2: Microturbine System with a Rear-Mounted Recuperator (McDonald, 2003).

2.2 Microturbine Performance

- The general operating conditions for a microturbine are: the turbine inlet temperature 800 – 1000°C, and compressor and turbine efficiencies 82 and 83.5% respectively (Kesseli et al., 2003). Detailed operating conditions for a typical 50 kW first generation standalone microturbine system based on proven technology and a microturbine coupled with a fuel cell system are provided by (Massardo et al., 2002). These machines having radial flows (with smaller blade heights) and hence have lower efficiency and lower performance than the large machines with axial flows (long blades). Typical thermal efficiency of a simple cycle microturbine is about 20% at the pressure ratio of 4:1, and smaller at a lower pressure ratio. If a recuperator with effectiveness of 87% and higher is included in the cycle, the system efficiency is increased to about 30% and higher at a pressure ratio of about 4:1 and hence a recuperator is essential in a microturbine. 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% with recuperated microturbines, the increase in the efficiency and a reduction in specific fuel consumption of microturbines is depicted in Fig. 3. As one can find, the long term projection for thermal efficiency of a microturbine system is about 50% using a ceramic recuperator with effectiveness of 95% and the turbine inlet temperature of about 1750°C.

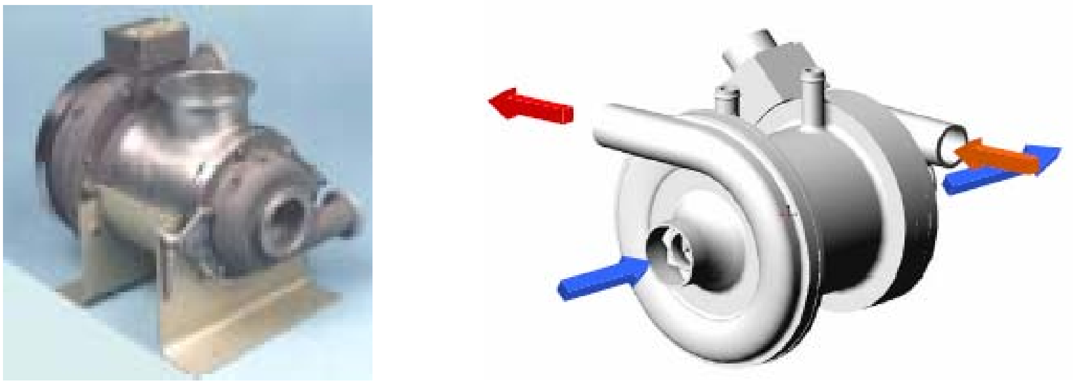

Figure 3: Honeywell Turbocompressor Development from the First Generation to the Latest (Ordonez et al., 2004).

2.3 Microturbine Technology Status

Microturbine development started in 1990. However, we will briefly present the turbomachinary development.

Honeywell (Ordonez et al., 2004) has been developing turbomachinary (turbocompressor) since early 1960s for military and aviation applications: Honeywell has also developed compact foil bearing technology with over 30 years of experience, 80,000 hours of continuous operation and 50,000 starts/ stops. This foil air bearing turbocompressor has been used in the aforementioned turbomachinary and in a number of fuel cell applications: 5 MW phosphoric acid fuel cell power plant in 1981, 50 kW DOE PEM fuel cell system for light duty vehicle in 1997 and 2003, another DOE 50 kW PEM fuel cell system in 2001 and unmanned aerial vehicle in 2003.

Honeywell fuel cell turbocompressor as shown in Fig. 4a is light weight (<15 kg or 15 liters), efficient ($\eta c = 75\%$ and $\eta t = 80\%$), reliable (since only one moving part), having zero maintenance, high temperature capable and in modular form. This turbocompressor is further being developed as shown in Fig. 4. Phase IV will be completed at the end of 2005. This turbocompressor will have the following performance at 2.5:1 pressure ratio and 100 g/s airflow: compressor with 72% efficiency, expander/turbine with 80% efficiency and a variable nozzle, 6 kW with turbine assist and up to 15 kW during startup/transient. By 2010, this turbocompressor will be further refined so that compressor will have 80% efficiency and the turbine will have 85% efficiency. The projected cost will be $400/unit for 100,000 units/year production.

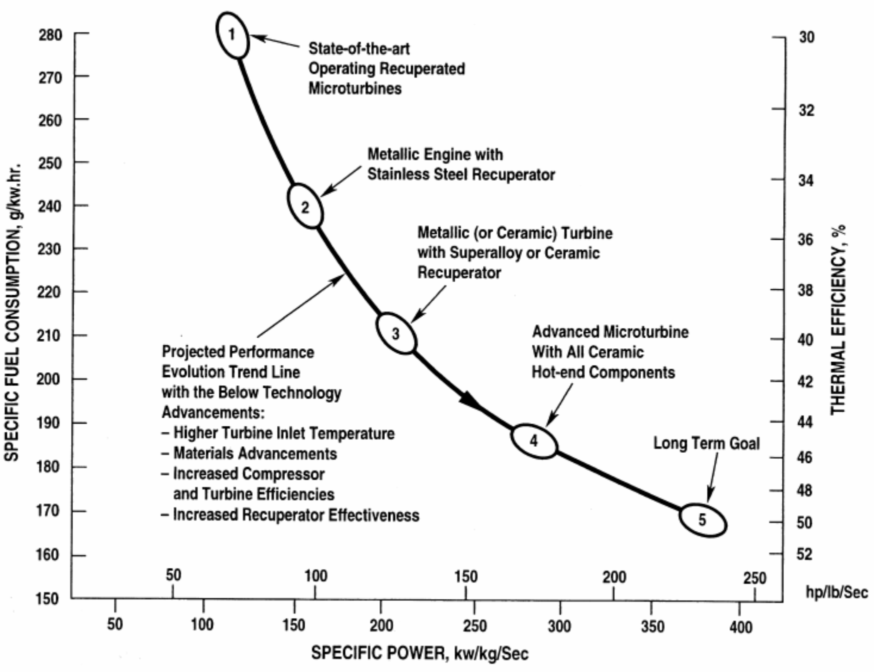

Figure 4: Microturbine Performance Projection (Massardo et al., 2002).

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

3.0 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 with minimum cost. The desired performance requirements for microturbine recuperators are summarized in Table 1 by McDonald (2000b), and those by 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 steep temperature transients during startup and shutdowns.
- Desired 40,000 hour operation life without any maintenance for stationary power generation applications. This would translate in good thermal shock, corrosion, oxidation and creep resistance and low thermal expansion.
- Compact (means small hydraulic diameter surfaces) and lightweight matrix with integral manifolds (having low pressure drop and uniform flow distribution), and mass producible low cost design.

Table 1: Microturbine Recuperator Requirements

Major design criteria	Low heat exchanger cost Meet demanding microturbine performance and economic goals High recuperator reliability
Performance	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
Fabrication	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 construction	Compact and light weight matrix Integral manifolds/headers Matrix envelope flexibility (annular or platular)
Cost	No basic material wastage 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 and fatigue failure for design life Remain leak tight for engine life Life goal of 50,000 h for microturbine generator sets
Installation	Gas flow path compatibility with turbomachinery Compact and light weight overall assembly Eliminate inter-connecting ducts Eliminate need for thermal expansion devices
Maintenance	Ease of recuperator removal/replacement Plug-in matrix cartridge (analogous to oil filter element) Ease of leak detection testing Ease of weld repair
Performance 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 & 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)

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 will be no brazing (a costly manufacturing process).

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

4.0 RECUPERATOR DEVELOPMENT

The 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 element analysis program. If thermal stresses 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 analysis and test results.

5.0 RECUPERATOR STATE-OF-THE ART TECHNOLOGY

In this section, we will summarize various heat transfer surfaces contemplated and used over the years for the gas turbine technology 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 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: compact design with good aerodynamic gas flow path having low pressure drop, lower acoustic signature, built-in rotor burst shield, and no need for external ducts and thermal expansion device. The advantages of cube-shaped recuperator are: simplicity for hot gas bypass for cogeneration, external combustor for a variety of dirty

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[†] 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).

fuels, and the coupling of recuperated microturbine and 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 rounded off recuperator material cost would be about $500 (McDonald, 2000).

While the plate-fin recuperator technology and manufacturing processes are known, there is good design flexibility and the recuperator would be light weight. There are some important limitations for the plate-fin design: high material and 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.

5.1 Plate Type Primary Surface Recuperators

The noncircular plate type primary surfaces have been used by heat exchanger industries long before its use in gas turbine application 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 since the other fluid side had high heat transfer coefficient (so that the exchanger becomes compact for space considerations), and there was no cost pressure. Hence, the development of extended surfaces was accelerated by developing plate-fin surfaces after the invention/introduction of salt-dip brazing technology in late 1930s. Due to environmental concerns, salt dip brazing was replaced by vacuum brazing technology in early 1980s, and the neutral environment (NOKOLOCK) atmospheric brazing technique in mid 1980s.

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 airside, which necessitates the use of fins on the gas side for a balanced heat exchanger. Hence, the use of all primary surface recuperator 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 foil of metals (i.e., a stack of formed plates) can be formed in 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 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 bi-metals to have 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

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[†] 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.

primary surfaces having fin efficiency of 100%, i.e., the surfaces are fully effective from heat transfer point of view.

Solar Turbines, Caterpiller and Capstone Turbine Corporation companies of USA have manufactured several thousands of 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 0.100 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 of 60,000 rpm. At 45,000 rpm, the maximum inlet temperature to the recuperator is 843°C.

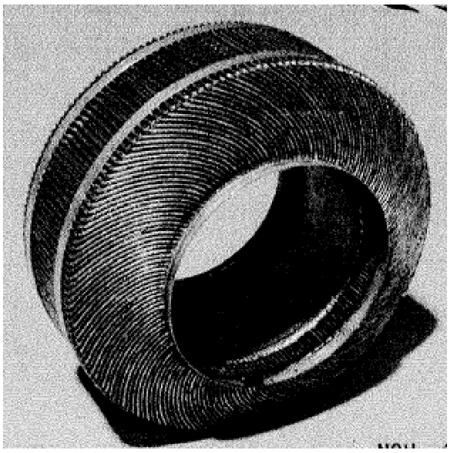
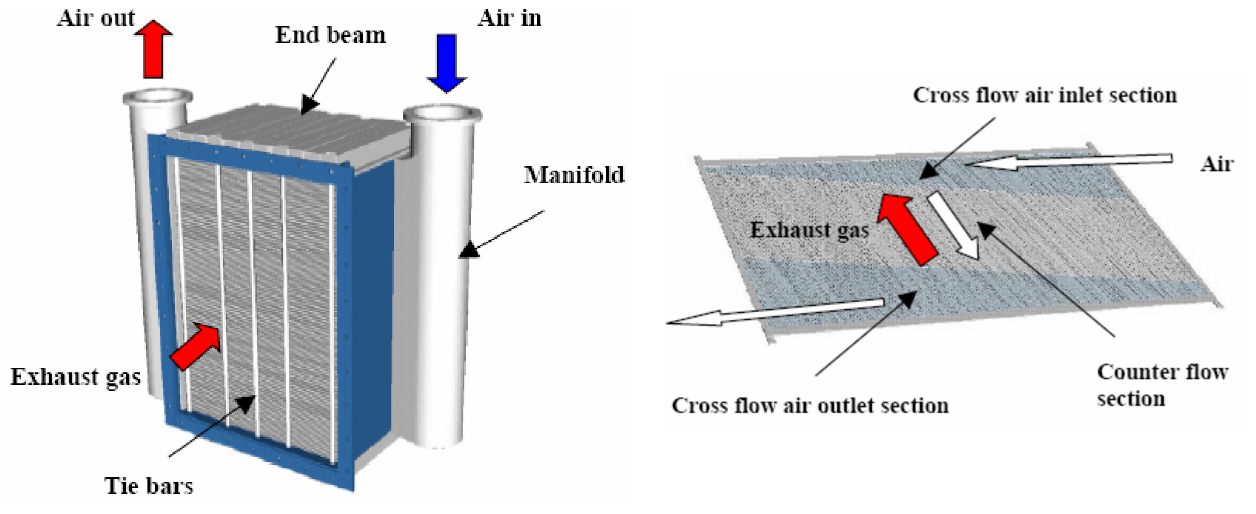


Figure 5: Annular Primary Surface Stainless Steel Recuperator from Solar Turbines, Inc. (Treece et al., 2002).

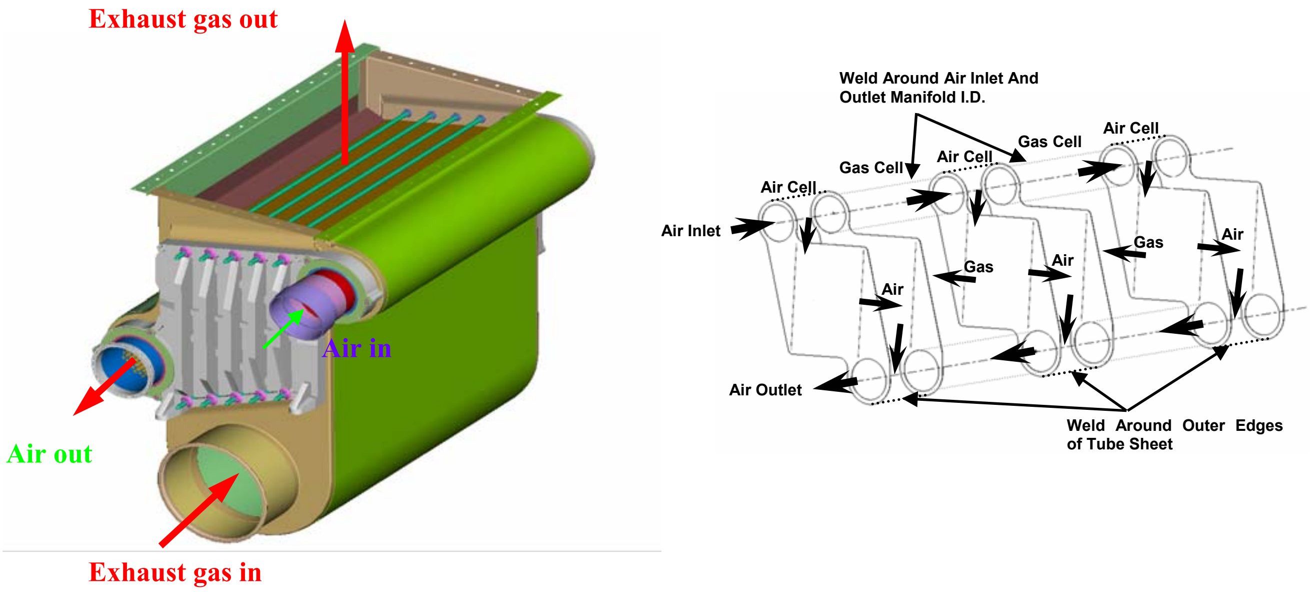
Rekuperator Svenska AB of Sweden (Lagerström and Xie, 2002) has developed a primary surface recuperator having thin corrugated austenitic stainless steel plates; two such plates are laser welded around the perimeter of two opposite sides to make a flow passage for air flow. Such plate assembly has two 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 Δp/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.



(a) (b)

Figure 6: (a) Rekuperator Svenska Primary Surface Recuperator, and (b) a Typical Air Passage Geometry (Lagerström and Xie, 2002).

Muley and Sundén (2003) describe a prime surface counterflow (with crossflow headers) recuperator developed by Honeywell Corporation. The construction features are shown in Fig. 7. The plates have corrugation in heat transfer region, and inlet and outlet manifolds, all made in a single die operation. These plates are welded at 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.



(a) (b)

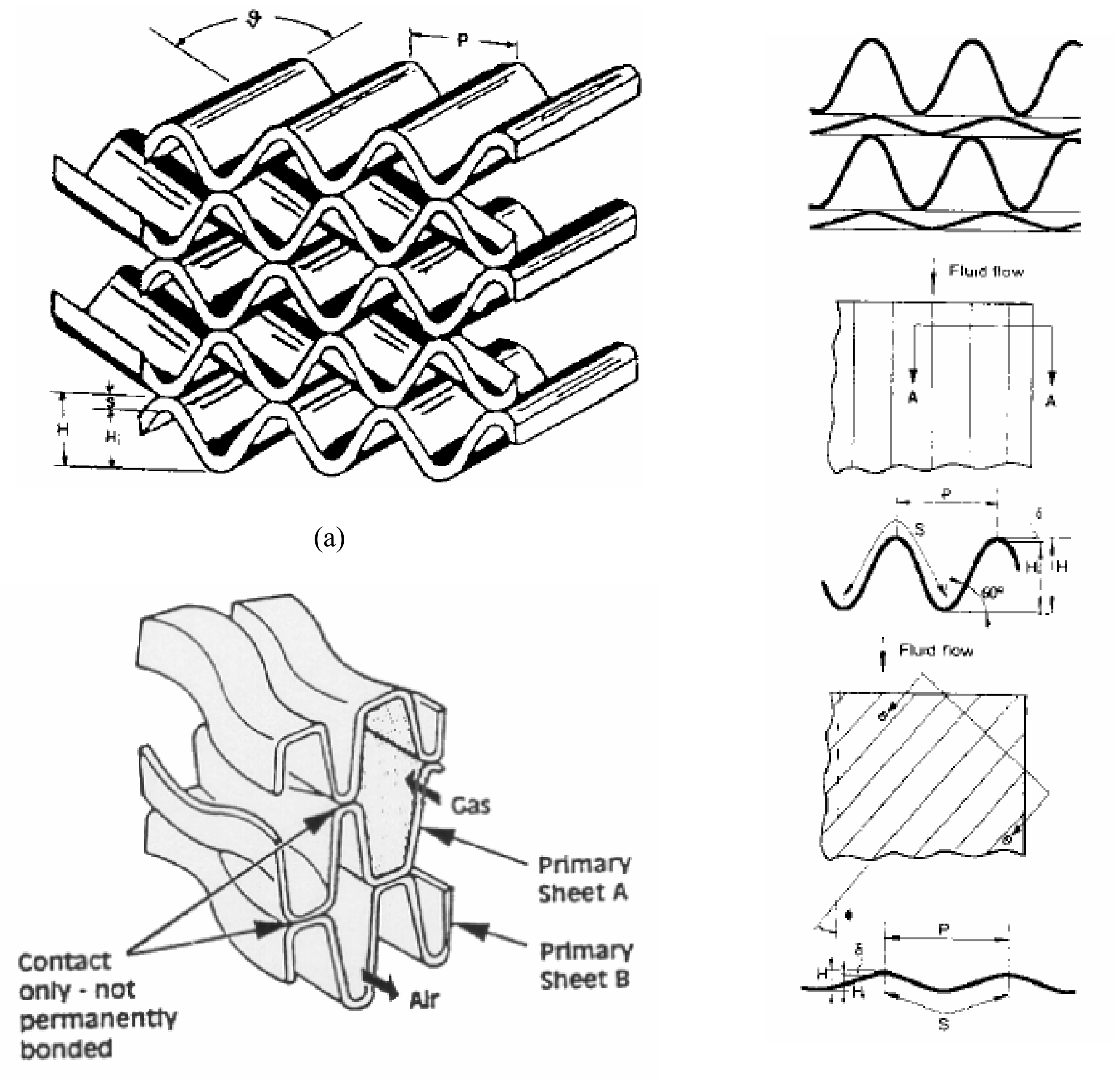
Figure 7: (a) Honeywell Prime Surface Recuperator, and (b) Details of the Core Construction (Shah and Muley, 2002).

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 details 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 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 vehicular gas turbine engine power plant. In this application, 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 process due to high height and small pitch; it is 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.

[†] 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.



(a)

(c)

(b)

Figure 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).

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 by numerically for the CU and CW surfaces (Utriainen and Sundén, 2001). Utriainen and Sundén recommend the CC surface having best potential for use in compact recuperators of the future.

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

5.2 Tubular Primary Surface Recuperators

Tubular primary surface has the advantage of containing high pressure fluid within the tube with the 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 disadvantage of a circular tube core are: it has the lowest 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).

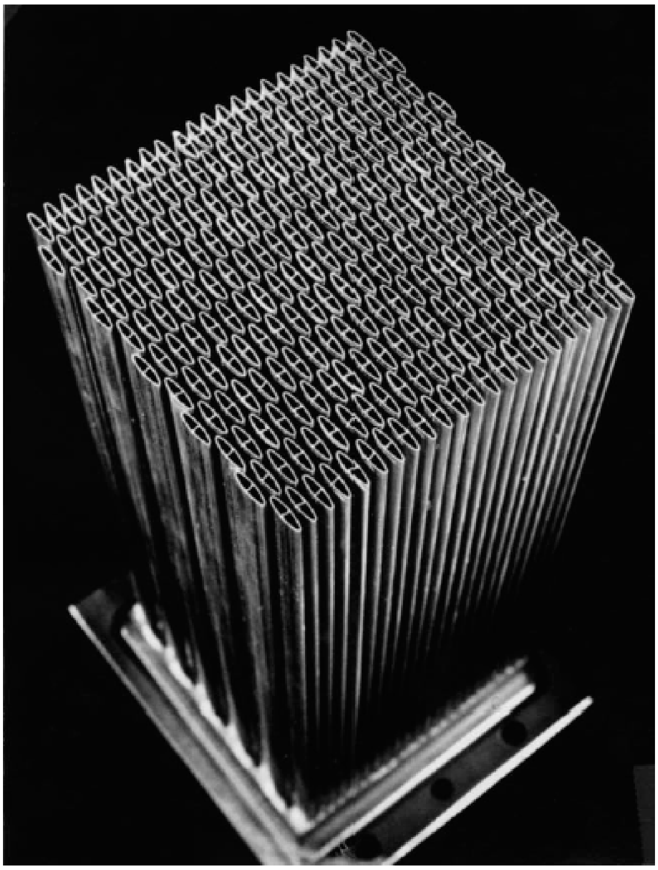


Figure 9: Elliptical Tube Recuperator (McDonald, 2003).

5.3 Extended Surface Recuperators

Brazed plate-fin recuperators have been used by industry from over 50 years for a variety of applications. Initially, the salt-dip brazing technology was used followed by vacuum and neutral environment brazing in 1980s. 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.

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 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 (1) Optimum pressure ratio for maximum recuperated turbine shaft thermal efficiency is dependent on the turbine inlet temperature. For microturbines, this optimum pressure ratio is about 4 at turbine inlet temperature of 800 – 900°C. The recuperator core cost reduces drastically for increasing specific power kJ/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 going above 700°C, there is a step function change in the recuperator core cost due to the use of Inconel 625 in addition 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.

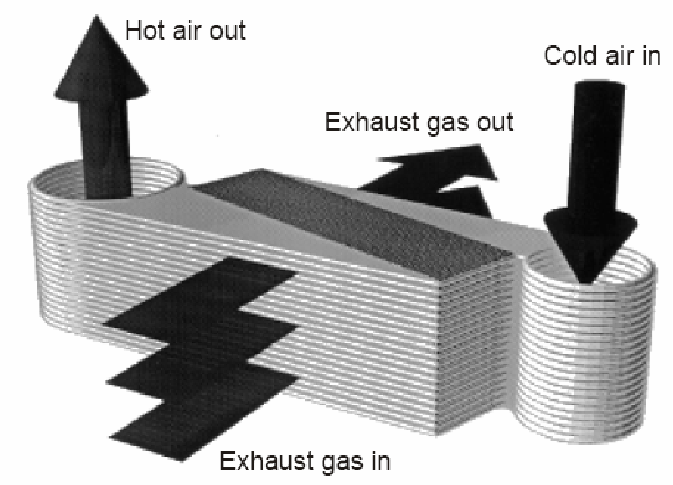


Figure 10: Recuperator Sketch showing Flow Paths. Manifolds for cold air entering and hot air leaving the recuperator are created by welded circular flanges (Kesseli et al., 2003).

5.4 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. Hi 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 candid 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.

5.5 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 engine with a microturbine generating electricity at the maximum efficiency and the hybrid vehicle then running on the electricity or direct-drive vehicles. For an automotive application with 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, low-cost manufacturing methods and easy to replace or maintain (McDonald and Wilson, 1996).

6.0 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). 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 concludes that a gas turbine cycle with a high effectiveness regenerator can reach to 50% electric efficiency for microturbines of 300 kW and over.

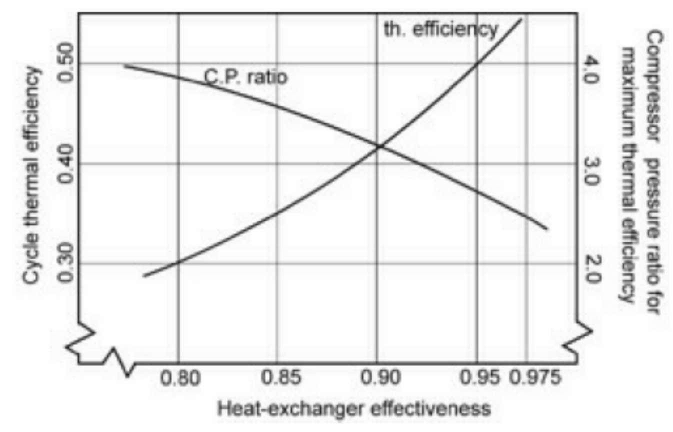


Figure 11: The Gas Turbine Cycle Thermal Efficiency and Optimum Pressure Ratio as a Function of the Heat Exchanger Effectiveness (Wilson, 2003).

7.0 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.

7.1 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. Existing one of the highest performing surface is 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).

7.2 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 and the cost increase significantly (3 – 5 times). 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 was 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.

8.0 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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