Bernard F. Kolanowski, BSME

GUIDE TO MICROTURBINES

Guide to Microturbines

Bernard F. Kolanowski, BSME

THE FAIRMONT PRESS, INC.
Lilburn, Georgia

MARCEL DEKKER, INC.
New York and Basel

MARCEL DEKKER

Library of Congress Cataloging-in-Publication Data

Kolanowski, Bernard F.
Guide to microturbines / Bernard F. Kolanowski
p. cm.
ISBN 0-88173-418-7 (print) -- ISBN 0-88173-426-8 (electronic)
1. Gas-turbine power-plants. I. Title.

TK1076.K66 2004
621.1'99--dc22

2004046904

Guide to microturbines/Bernard F. Kolanowski.

Fairmont Press, Inc.
700 Indian Trail, Lilburn, GA 30047
tel: 770-925-9388; fax: 770-381-9865
http://www.fairmontpress.com

Distributed by Marcel Dekker, Inc.
270 Madison Avenue, New York, NY 10016
tel: 212-696-9000; fax: 212-685-4540
http://www.dekker.com

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

0-88173-418-7 (The Fairmont Press, Inc.)
0-8247-4001-7 (Marcel Dekker, Inc.)

Guide to Microturbines

Dedication

I couldn't have written this book without the encouragement of Mr. Bill Payne, former editor of *Cogeneration and Competitive Power Journal*, and his recommendation to the publisher to see such a book published. I hope I've confirmed Bill's confidence in me.

AND

To my considerate wife, Mary Beth, who allowed me to take time away from her to accomplish this.

Acknowledgments

The following companies and individuals have contributed to this book:

Mr. Robin Mackay
Bowman Power Systems
Capstone Turbine Corporation
Elliott Energy Systems
Ingersoll-Rand Power Works
Turbec AB
Toyota Turbine Co.
ALM Turbine Co.
Orkas Energy Endurance and Dr. Ake Almgren
Mr. Jim Clyde

Table of Contents

Chapter 1

Introduction and History of The Microturbine

I WAS THERE at the birth of the microturbine. North American Cogeneration was owned by Herb Ratch who knew Robin MacKay and Jim Noe, two engineers that had left Garrett Corporation after it had merged with Allied Signal. Robin and Jim decided to form a company to develop a small gas turbine that might be useful in the automotive market. This was in 1988 when NoMac Energy came into being.

Funding was important to NoMac and they decided to solicit a grant from the Gas Research Institute for those funds. Robin asked Herb to help prepare the proposal to the GRI and as I was then representing North American Cogeneration, they solicited my help in doing some of the writing. A prototype machine had already been manufactured by NoMac and I not only held many of the key component parts in my hands, I saw the first microturbine in operation at NoMac's facility. Little did I know that some 10 years later the microturbine would be such an instrumental part of my future.

It's believed the word "microturbine" evolved from the fact that it is a true gas turbine demonstrating all the characteristics of a gas turbine, but simply smaller in power output. No formal boundary exists as to when a gas turbine becomes a microturbine or vice-versa. However, it is generally accepted that zero to 300 kilowatts is the "range" of the microturbine. Pratt & Whitney gave this credence when they developed their 400 kilowatt unit and called it a "mini turbine!"

NoMac's company evolved into what is today the Capstone Turbine Company headquartered in Chatsworth, CA. While Capstone is rightly considered the originator of today's microturbine, it was not until December of 1998 when commercially available and reliable units were finally marketed. An elaborate article in the April 1, 1996 issue of Fortune Magazine prematurely touted the advent of this "pint-sized power house." False starts plagued Capstone, mostly in the power electronics area, before they finally solved the problems. After all, getting 60 hertz, AC current from a generator spinning at 96,000 rpm was no mean trick.

So, the microturbine is a recent development. The vast majority of gas turbines today are jet engines, turboprops or turboshaft engines. Renowned for their high power to weight ratio, extreme reliability and low maintenance, these engines dominate the aircraft industry. Derivatives of these turbines drive electric utility generators, power pipeline compressors and propel ships. A separate class of industrial gas turbines is used in power generation and other heavy duty applications. Almost all of these industrial gas turbines, however, are rated in the thousands or tens of thousands of kilowatts with more than a few over a hundred thousand kW. The microturbine has many big cousins, but it is a gas turbine extolling the same advantages as those brawny brutes.

The one noted advantage, however, is the ultra-low emissions that the microturbine emits. One disadvantage is that the small size of the compressor and turbine wheels limits the component efficiency, holds down the pressure ratio and prevents the turbine wheel from being internally cooled. Thus, the efficiency of a small, simple cycle gas turbine is well below that of a reciprocating engine—14% vs. 40%. Small production quantities have meant relatively high prices compared to the 100-year-old reciprocating engine that is installed in virtually every moving vehicle driving down the highway. These two factors have limited market penetration.

EVOLUTION

The primary application for small gas turbines has been in the aircraft industry. Most commercial and military airplanes use pneumatic starters to start their jet engines or turboprops. Most air conditioning on these aircraft is air cycle and requires a source of clean, oil free, compressed air. Simultaneously electric power is needed. Accordingly, gas turbines were developed that have oversize compressors that can be bled to provide the needed compressed air. At the same time the gas turbine drives an alternator through a reduction gearbox to provide electricity that is typically 400 hertz.

When these auxiliary power units, APUs, are installed in an aircraft, the low weight, low maintenance and high reliability overcome any concerns about high cost and fuel consumption, especially since the operating hours are few.

In the early 1960s The Garrett Corporation adapted two of their 85 series APUs to run on natural gas and drive 200 kW generator sets. Equipped with exhaust heat boilers, they were installed in one of the early gas turbine-driven cogeneration systems. With the concept proven, Garrett then developed the 831 series industrial gas turbines that were derived from their 331 series turboprop engines. Initially rated at 218 kW, the rating was eventually increased to 515 kW. Several hundred of these units were installed in a wide variety of cogeneration systems. Reliability was extremely high and systems were installed to provide precise power for the central computer systems of United, Continental and Western airlines as well as the United States Air Force Automated Data Weather System and also at a savings and loan institution.

The Boeing Company designed some of the first small gas turbines during World War II. This was an exercise to learn the characteristics of gas turbines when Boeing started the design of the B-47. Although this was a six engine jet propelled bomber, it was originally planned to be a turboprop. Hence, Boeing's small gas turbine had an output shaft. Indeed, this was the first free turbine engine. Separate turbine wheels drove the compressor and the output shaft. Thus, the output shaft speed could be varied all the way down to stall.

The U.S. Navy noticed that the Boeing 502s were primarily stainless steel and aluminum and thus had no magnetic signature. They purchased several hundred for mine sweepers. During the late 1950s and early 1960s, Boeing pioneered many gas turbine-powered applications such as anti-submarine drone helicopters, an oil cementing truck, a bulldozer, fire engines, a fire boat, high speed launches, army tanks and even an Indianapolis race car. Two were delivered for installation in a Thunderbird and a Fairlane. Many were used to provide compressed air to start 707s, DC-8s and other aircraft that did not have auxiliary power units.

The first cogeneration system powered solely by gas turbines was installed at Southern California Gas Company in their Downey, CA, facility in 1962. The two gas turbines were Boeing 502s rated at 140 kW each.

Boeing even developed a 100 horsepower outboard motor. It was a technical triumph. It weighed 100 pounds less than the 80 horsepower conventional outboards that were the largest in production in those days. It also burned less fuel. However, Boeing was not in the consumer products business and the outboard program was terminated and three years later Boeing sold their gas turbine business to Caterpillar

During the 1960s many automobile companies developed prototype gas turbines for automobiles. Rover was the first. Chrysler put fifty units out in the field for testing. General Motors and Allison built several different models. Ford drove a truck across the United States powered by their gas turbine. Daimler Benz, Volkswagen, BMW, Toyota, Nissan and others all built gas turbines. To solve the fuel consumption problem, automotive gas turbines used heat exchangers to pre-heat the air going into the combustion chamber using the normally wasted heat in the exhaust. These heat exchangers were sometimes recuperators but more often regenerators. Whereas a recuperator is a simple fixed boundary heat exchanger, a regenerator is a wheel that rotates through the exhaust picking up heat, and through the compressor discharge where it preheats the air going to the combustor.

Regenerators are compact and effective. However, they are usually ceramic and have a problem with cracking. They also have a sealing problem as the wheel rotates through both atmospheric pressure exhaust and high pressure compressor discharge air. Problems with the regenerator, cost of production and turbo lag killed the automobile gas turbine. Turbo lag was a particular challenge. To lower fuel consumption when an automobile was stopped in traffic or at a red light, the rpm was lowered. When the light changed to green, power was limited until the turbine spooled up which could take several seconds. You can imagine the cacophony of horn sounds behind a turbine powered vehicle.

The most interesting vehicular gas turbine in those days was the Ford 705. It was essentially a turbocharged, recuperated gas turbine. It achieved an efficiency of over 36%, which was better than the diesels being sold in those days. However, it was not really a small gas turbine in that the two versions were rated at 300 and 600 horsepower. Unfortunately, cost was a problem and Ford reverted to conventional regenerated gas turbines.

The survivor in small gas turbines was The Garrett Corporation Garrett was one of the Signal Companies. When Signal merged with Allied, Garrett became part of AlliedSignal Aerospace. When AlliedSignal bought Honeywell and adopted the Honeywell name, Garrett became part of Honeywell.

The two largest divisions of Garrett were the ArResearch Manufacturing Company of Arizona located in Phoenix, and the AiResearch Manufacturing Company of Los Angeles originally located in Los Angeles and later in Torrance. Phoenix was the dominant manufacturer of small gas turbines with many tens of thousands of units installed as auxiliary power units on board aircraft and in ground carts. The 831 series gas turbines discussed above were built by Phoenix. However, it was Torrance where the precursors to the modern microturbine were developed.

Torrance was by far the largest manufacturer of aerospace environmental control systems. They are used for air conditioning and heating commercial and military aircraft. Most of these units are air cycle and include high efficiency compressors and turbines mounted on fluid process bearings commonly known as air bearings. These bearings require no lubricants and no outside source of compressed air.

Torrance also built high-speed generator, high-speed refrigerant compressors, recuperators and gas turbine control systems. With support from the gas industry and the Department of Energy, Torrance used their expertise to develop prototypes of a radical new 10 ton heat pump in the 1970s. A 12 horsepower, natural gas fueled, recuperated gas turbine was used to drive a centrifugal refrigerant compressor which replaced the electrically driven compressor in a conventional heat pump. To keep the refrigeration system hermetic, the gas turbine drove the compressor through a magnetic coupling. To eliminate the need for a natural gas compressor and to enlarge the components so that they could be more efficient, a subatmospheric cycle was used.

In a conventional recuperated cycle gas turbine, outside air is compressed, preheated in the high pressure side of a recuperator, heated to higher temperature in a combustor and expanded through a turbine wheel, which powers both the compressor and the load. It then enters the low pressure side of the recuperator where heat is transferred to the high pressure side of the recuperator.

Subatmospheric cycles are different in that outside air enters the high pressure side of the recuperator first. The air is preheated in the recuperator, further heated in the combustor and expanded into a partial vacuum in the turbine, which drives both the compressor and the load. As in the conventional cycle, the air then enters the low pressure side of the recuperator where heat is transferred to the high pressure side of the recuperator. The air then enters the compressor, which sustains the partial vacuum before being discharged to atmosphere.

The conventional cycle and the subatmospheric cycle use essentially the same components. Both are Brayton cycles, the difference being where the air enters and leaves the cycle. The key advantage of the subatmospheric cycle is that the combustor is at, or very slightly below, atmospheric pressure. Thus, natural gas at normal delivery pressures will flow into it and there is no need for a fuel gas compressor, which is expensive and generally inefficient.

The second advantage is that the power output is reduced by a factor approximately equal to the pressure ratio. Thus, in a very small gas turbine the compressor and turbine are significantly larger and therefore have higher component efficiencies. In larger units, this becomes a disadvantage as the power available for a given piece of turbomachinery is reduced. Another way to look at subatmospheric cycles is that its performance is essentially the same as that of a conventional cycle that is operating at altitude.

Prototypes of the 10-ton heat pump achieved high levels of performance. They also demonstrated the feasibility of the subatmospheric cycle. The power unit was the first example of a gas turbine designed for production that ran on air bearings and required no lubrication and no source of compressed air. These bearings are ideally suited for high speed machinery where there are no gears because the load is driven at the same speed as the gas turbine. No power take-off is needed to drive an oil pump. Indeed, there is no oil pump, no oil sump, no oil cooler, no oil changes and no need to top off or check oil levels. Similarly, with no water cooling requirements, elimination of open or closed water cooling systems and the attendant treatment, pump and maintenance problems were also eliminated.

The prototypes proved the concept and demonstrated the performance. Unfortunately, government studies erroneously claimed that natural gas would be in short supply and that the price of natural gas would dramatically increase relative to the price of electricity. This would cripple the economics of gas fueled heat pumps and the program was discontinued. The fact that natural gas prices and electric prices followed the same curve in many parts of the country was mitigated when most public utilities were regulated and could not readily change their rates despite higher fuel costs. In this day of de-regulation of power companies, that factor would be less of a hindrance to marketing natural gas fueled technology.

Smaller, three ton heat pumps were also developed at Torrance for the residential market, but suffered a similar fate even though the concept included a bottoming cycle, which increased the output and the efficiency by about fifteen percent. Because the cycle was subatmospheric, the exhaust discharged out of the compressor. The exhaust was hot because of the heat of compression. Thus liquid refrigerant from the heat pump could be pumped up to pressure and vaporized in the gas turbine's exhaust. It could then be expanded through a turbine wheel that would be mounted on the back of the refrigerant compressor. The turbine wheel would then discharge the expanded refrigerant into the same condenser that the refrigerant compressor discharged into. As both wheels used the same refrigerant, small amounts of leakage did not matter.

The method of starting such a system was interesting. In a conventional gas turbine-driven generator set, the generator can be used as a starter motor. But there was no generator in this concept. However, there was liquid refrigerant and a refrigerant turbine wheel. Thus liquid refrigerant could be contained and heated until it vaporized using an electric resistance hater. This vaporized refrigerant could then be suddenly released to flow through the refrigerant turbine wheel causing it to spin up. As the refrigerant turbine was connected to the gas turbine through the magnetic coupling, the gas turbine would also spin up and would start.

When the energy crisis eased and it was realized that natural gas would be available, Torrance started on the design of the Advanced Energy System or AES. Basically, it was a recuperated gas turbine-driven generator set rated at 50 kW. It used a conventional rather than a subatmospheric cycle. The rotating group consisted of a permanent magnet with a compressor wheel mounted on one end and a turbine wheel mounted on the other end. The rotor group ran on air bearings so no lubrication was needed. Other than cooling fans and a fuel pump or natural gas compressor, this assembly was the only moving part in the system.

With an eye on fuel consumption, the AES had a recuperator. This heat exchanger transferred heat from the hot turbine exhaust to the compressed air entering the combustor. Thus the combustor needed less fuel to bring the air up to the required temperature. Fuel consumption was cut roughly in half compared with a gas turbine without a recuperator. However, there was still a lot of heat left in the exhaust. Making use of this energy for heating or cooling a building or for an industrial process such as drying could raise the system efficiency up into the 80% range.

Prototypes ran well. However, the Signal Companies merged with Allied and became AlliedSignal, as mentioned above. The Garrett divisions in Torrance and Phoenix became part of AlliedSignal Aerospace. The non-aerospace, non-military projects were terminated and the AES became an APU where it was installed in an army tank as a demonstration. Interestingly enough, AlliedSignal returned to this field several years later to develop the Parallon microturbine, the rights of which were sold to General Electric.

Robin MacKay had been instrumental in many of these programs. At Boeing, he initiated, sold and installed the cogeneration and oil field systems. He also worked on the outboard motor. At Garrett, he was responsible for most of the cogeneration sales and developed the concepts for the two subatmospheric gas turbine programs and the Advance Energy System. He wrote numerous papers and held several patents.

FULFILLMENT

MacKay took early retirement from what was now AlliedSignal and contacted Jim Noe who had been in engineering at Garrett, had worked with MacKay on several projects and held various patents on air conditioning and on subatmospheric gas turbines. Thus was the start of NoMac in 1988. Fortunately, AlliedSignal was gracious enough to grant NoMac licenses to some of the patents that had been issued to MacKay and Noe while they were at Garrett but were now assigned to AlliedSignal. The key patent licensed was the one for the residential heat pump that Garrett had designed but not built.

The company was very small. For the first five years it consisted of MacKay and Noe plus, intermittently, one engineer, one draftsman and one secretary. NoMac relied heavily on outside consultants for detailed design and analysis. NoMac also entered into joint venture with Tiernay Turbines called MTN Energy Systems. MTN stood for MacKay Tiernay Noe. Eventually, this joint venture was dissolved.

The original objective was to develop the residential heat pump with funding from the gas industry. The market for residential heat pumps and air conditioners was estimated to be in the six million units per year range. The projected coefficients of performance (COP) were 2.0 in the heating mode and 1.6 in the cooling mode. Thus, the units, if successful would have offered dramatic savings in both energy consumption and energy cost when compared with the best available units at the time.

A derivative version was also to be developed. The magnetic coupling and the refrigerant compressor and turbine were to be replaced with a generator. The objective was to build small generator sets in the three to six kilowatt range with the first applications aimed at the recreational vehicle market.

The gas industry was very enthusiastic about the potential of a very efficient gas fueled air conditioner. They were somewhat less enthusiastic about a very efficient gas fueled heating system that would only use half the gas that the best residential furnace then available used. Accordingly, the decision was made to increase the rating to 25 tons. The new markets were to be commercial establishments such as stores and factories where lots of air conditioning but very little heating would be needed.

With the increase in size, the subatmospheric cycle became less attractive and a conventional positive pressure cycle was