THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

84-GT-150

Cheng Cycle Implementation on a Small Gas Turbine Engine

R. Digumarthi

Chung-Nan Chang

International Power Technology,
Sunnyvale, Calif. 94086

The Cheng Cycle turbine engine is a superheated steam injected gas turbine cycle system. This work is based on the Garrett 831 gas turbine. The development effort involved the design and manufacture of an experimental heat recovery steam generator, a steam injection system, and system controls. Measured performance data indicate the 26 percent efficiency improvement has been obtained compared to that of the basic turbine engine at its continuous power rating.

1 Introduction

A couple of decades ago, fuel was cheap and the supply seemed so plentiful that incentives were lacking for the development of more efficient energy converters. Now as the situation has changed, even relatively modest increases in efficiency are economically attractive. The Cheng-Cycle turbine is an engine recently developed to meet the need for greater efficiency. This paper describes the development and experimental results of the Cheng-Cycle turbine based on a small gas turbine.

The Cheng Cycle, a patented thermodynamic power cycle of International Power Technology, combines the Brayton and the Rankine cycles in a unique manner, utilizing the exhaust heat in the form of superheated steam at a moderate pressure. This unique cycle was applied to the Garrett IE831 Engine consisting of a 600-kW generator packaged by Onan Corporation.

The Onan 560 Gtu set was attached with an experimental (Onan 560 Gtu Set) heat recovery steam generator (HRSG). This combination of the Garrett 831 turbine with the HRSG is a typical Cheng-Cycle turbine. This paper will show the development of Cheng-Cycle turbine involving the performance matching of the components, fabrication of the HRSG and the system control unit. The development of steam injection manifold will also be discussed. The comparison of the CC-Turbine performance and Brayton cycle will be discussed.

Water injection is a well-known method of augmenting the power output with some penality of inefficiency. The Cheng-Cycle engine was developed on a patented process by International Power Technology Inc. [1–4] in the period from 1976 to 1981. The working fluid in the turbine is thus a combination of combustion gases and superheated steam. Increasing the mass flow and the specific heat of the working fluid increase work output dramatically.

Dr. Cheng of International Power Technology, analyzed the thermodynamics of the cycle and discovered that an optimum occurred in efficiency at large steam to fuel ratios. At this optimum ratio, the overall efficiency of the engine increased significantly. In this condition, the engine has all the advantages of a Rankine-cycle steam turbine operating as a topping cycle from the exhaust of a Brayton-cycle turbine. The engine has the mechanical simplification of a single shaft output and no increase in rotating machinery.

The improvement in the power output is based on the increased mass flow through the turbine when compared with the compressor mass flow. The increased mass flow through turbine in return would require higher compressor pressure ratio. The improvement in the power generated in the turbine will more than offset the requirement of the compressor work for higher compressor pressure ratio. Thus the steam injected gas turbine would produce more power at a higher efficiency but would utilize the same rotating machinery. The steam injection into the combustion chamber also reduces the generation of No_x [5].

Additional fuel burned in the combustion chamber to bring the superheated steam to the turbine inlet temperature is offset by the increase in the power output. For the same fixed power output of the basic engine, the addition of the superheated steam reduces the turbine inlet temperature and thus increases the life of the gas turbine.

The presence of the superheated steam in the exhaust gas flow enables the HRSG to extract more heat for the same temperature drop of the exhaust gases. The ratio of the injected steam, generated from the exhaust heat, to the compressor inlet air flow is coupled to the cycle parameters. The HRSG surface area, the turbine exhaust gas temperature, along with the evaporator exit temperature pinch have critical influence in achieving the peak efficiency of the gas turbine.

An important economic factor is that the Cheng-Cycle engine can be constructed with minor modifications to existing gas turbines. The modification consists of a waste heat recovery steam generator to provide the superheated steam and the modification to the combustion chamber to provide for the controlled steam injection at the proper fuel and air mixture ratios.

Contributed by the Gas Turbine Division of The American Society of Mechanical Engineers for presentation at the 29th International Gas Turbine Conference and Exhibit, Amsterdam, The Netherlands, June 4–7, 1984. Manuscript received at ASME Headquarters January 9, 1984. Paper No. 84-GT-150.

Copies will be available until April 1985.

Discussion on this paper will be accepted at ASME Headquarters until October 1, 1984

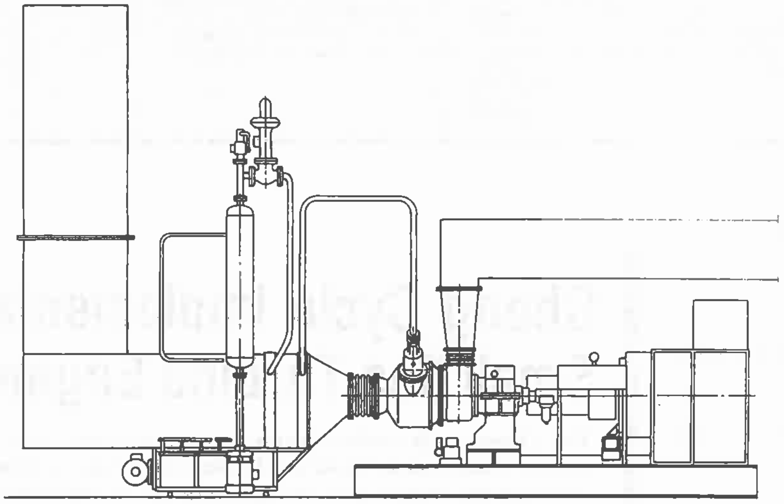


Fig. 1 Onan 560 GTU configured as Cheng-Cycle turbine

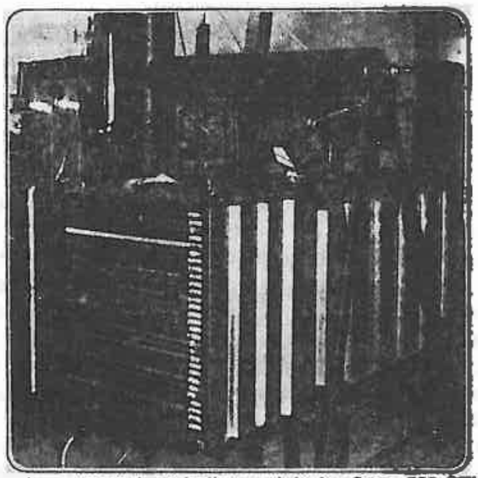


Fig. 2 Package waste heat boiler module for Onan 560 GTU Cheng-Cycle genset (superheater section in foreground is stainless steel fin tube, followed by conventional horizontal U-tube evaporator and economizer sections)

2 Onan 560-GTU (Garrett 831) Gas Turbine Generator

The 831 gas turbine is comprised of two radial outflow compressor stages with a single burner can with dual orifice atomizer for liquid fuel and a three-stage axial turbine. Though the 831 can utilize gaseous fuel, current experiments were conducted with liquid fuel DF-2 only.

The 831 turbine operates at a nominal compressor pressure ratio of 11 with 7.91bm/s of inlet air and turbine inlet temperature of 1760 °F. The Onan 560/Gtu Generator set consists of a Garrett IE831-800 gas turbine prime mover directly coupled to Onan "UV" generator. The gearbox is an integral part of the engine assembly, and the turbine speed is reduced to generator speed by double reduction spur gears. The generator is an Onan type "UV," 12-lead, 4-pole, revolving field, brushless unit wired for 277/480 volts, three-phase operation.

The Garrett IE831-800 gas turbine is an open-cycle, single-shaft, constant-speed gas turbine. Nominal rpm of 41,730 is reduced through the gear box to 1800 rpm as required by the generator. The Garrett 831 has a nominal shp rating of 800 shp as standby and 690 shp as continuous. With a nominal efficiency of 94 percent of the gearbox, the Onan-560 generates 560 kW at standby and 490 kW at continuous operation.

The Onan-560 generator set is equipped with relay control logic to provide basic operational control, fault shutdown of the gas turbine, and proper sequencing of the engine electrical system. This control system was utilized as local controller in the control schematic.

Based on the engine basic characteristics and assumed matching HRSG performance, the maximum operating characteristics of Cheng Cycle Turbine of 1-MW output at a thermal efficiency of 34 percent was projected at standard condition. A comparable thermal efficiency of 22.5 at the nominal rating of 520 kW was also predicted.

3 Steam Generating and Injection Equipment

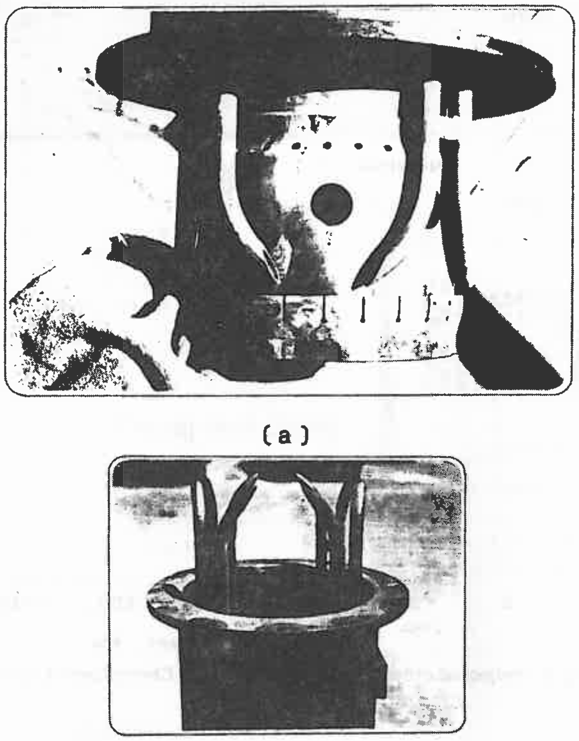
3.1 Heat Recovery Steam Generator. The heat recovery steam generator consists of superheater, evaporator, and economizer/feed water heater (Fig. 2). City water was fed through deionizing system before being pumped into the feedwater heater. The feedwater heater is one bank of crossflow heat exchanger. The water was then fed into an evaporator drum through a control valve. The evaporator consisted of four crossflow heat exchanger banks that were fed by a common header. The flow from the evaporator sections was fed into a vertical steam separator. The saturated steam was then separated into the superheater. The superheater steam was injected into the combustor can and the steam flow was measured utilizing an orifice meter and a vortex shedding meter.

The maximum operating pressure of the drum is about 200 psig. This pressure range was enough to maintain a 20 psi higher drum pressure than the compressor discharge pressure at the maximum operating point. The HRSG can generate a maximum of 3000 lbs/hr steam based on the surface area.

3.2 Steam Injection Manifold. The superheated steam from the HRSG was injected in the outer annules around the combustion chamber. The injection was made through eight steam tube nozzles in the secondary dilution region, with the nozzle pointing towards the compressor discharge region. The nozzle set up with the combustion chamber is shown in Fig. 3. With the steam tubes pointing in circumferential direction, the compressor discharge air has enhanced mixing of the injected steam.

4 Test Facility

The experiment was monitored utilizing the HP-9835. The software required for the data acquisition system was generated in-house. The software provides the opportunity to


(a)

(b)

Fig. 3 Steam injection nozzle arrangement

monitor 80 data channels. In this experiment, only 40 channels were utilized and the collected data were stored on floppy disks and displayed on a graphic screen showing the current state of the experiment.

The Onan 560 turbine generator was loaded using a resistance load bank. The load on the system was changed in 50-kW steps and was increased in a linear fashion. The voltage and the amperage at the load was monitored.

5 Experimental Results

The turbine generator was run at a various load and ambient conditions. It was found that the results were insensitive to ambient conditions over the range investigated.

Figure 4 shows the generating efficiency of the system as a function of power output for loads up to 500 kW, and for a variety of ambient temperatures ranging from 60 to 90 °F. Generating efficiency increased from about 9 percent at the 100-kW load to nearly 27 percent of the 500-kW load. The results are practically independent of the ambient temperature.

For comparison, the nominal engine efficiency operating in the usual Brayton-cycle mode, is also shown in Fig. 4. The Cheng-Cycle operation gives a significant increase in efficiency at all loads; for example, at the 400-kW load efficiency has increased from 17.5 percent for the usual Brayton-cycle operation to about 23 percent in the Cheng-Cycle operation, an increase of 31 percent in the relative efficiency.

It may be noted that calculations of thermal efficiency, using 94 percent as the combined gear box/generator efficiency, gives almost the identical curve. Efficiency and power output are both slightly increased by the correction, such that the functional relation remains nearly the same.

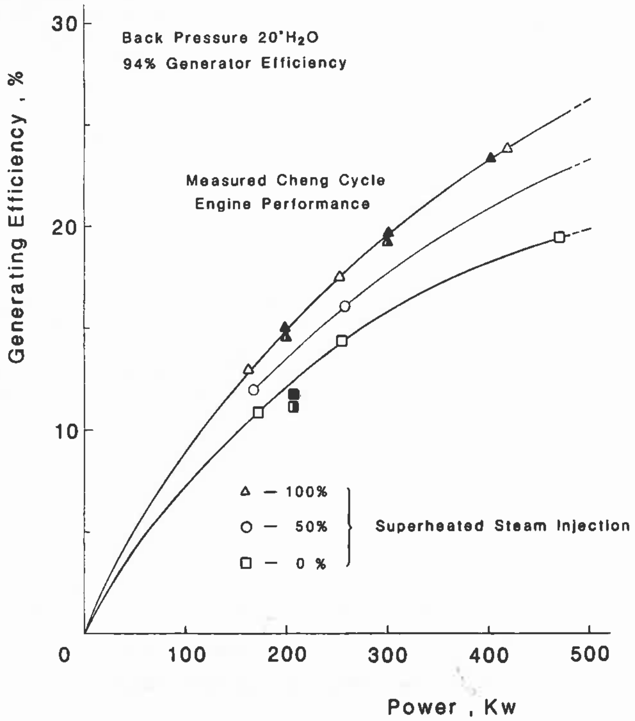


Fig. 4 Comparison of Cheng-Cycle turbine with basic turbine (△, □: $T_a = 60°F$; ▲, ■: $T_a = 80°F$; ▲, ◨ : $T_a = 90°F$)

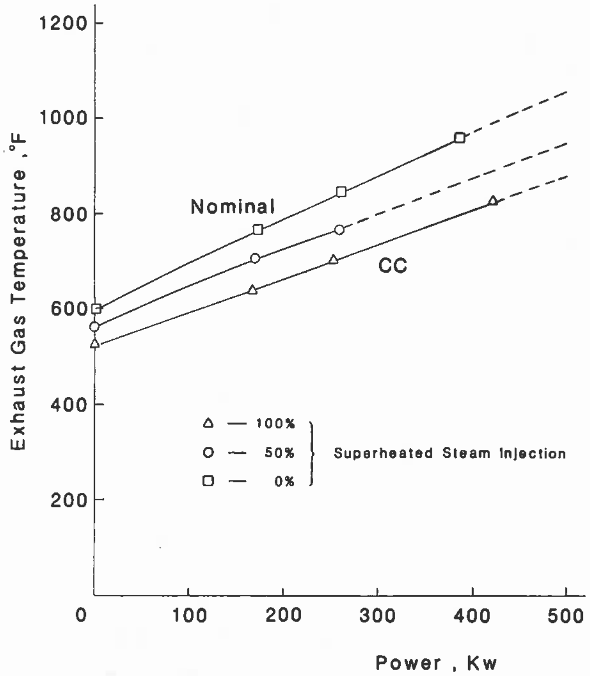


Fig. 5 Comparison of the exhaust flow temperature between Cheng-Cycle turbine and basic turbine

One of the important characteristics of turbine operation is exhaust temperature. Figure 5 shows the measured exhaust temperature for the Cheng-Cycle operation of the test unit as a function of power output. The nominal Brayton-cycle exhaust temperature is also shown for comparison. The Cheng-Cycle exhaust flow was 50°F cooler at low loads to nearly 100°F cooler at 400 kW.

For turbines, the crucial factor is generally the fuel cost, since initial capital cost is not such a large factor as for other types of energy converters. Figure 6 shows the percentage fuel saved as a function of load for the Cheng-Cycle operation compared with the nominal Brayton-cycle operation of the engine. The fuel saving varies from 10 percent at idle to 25 percent at the rated basic engine full continuous load.

A matched heat exchanger steam generator design would

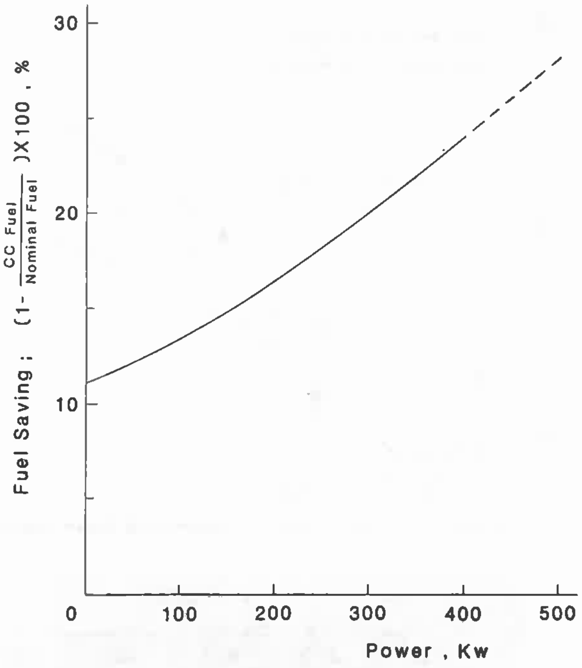


Fig. 6 Fuel saving for Cheng-Cycle turbine

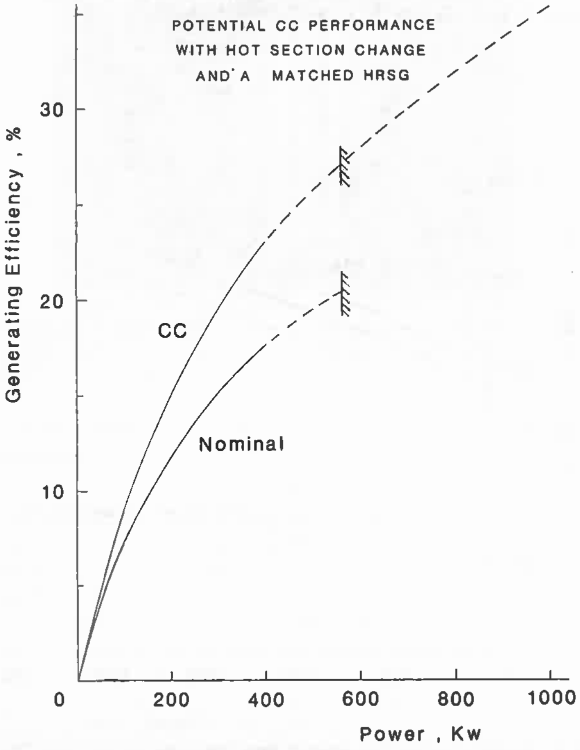


Fig. 7 Projected performance of Cheng-Cycle turbine

allow the turbine to operate at still higher load values. Peak power output could be increased from 560 kW to an estimated 1.1 MW with a thermal efficiency of 34 percent. This means that capital investment per kW-hour peak load could be reduced as much as a factor of 2 for this unit, as the modification costs are modest. The Cheng-Cycle modification thus renders smaller turbines attractive for higher load handling duty.

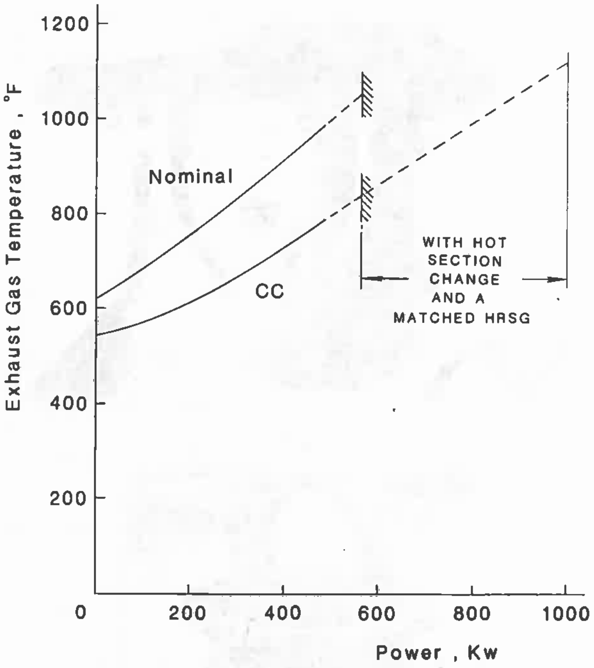


Fig. 8 Projected exhaust flow temperature for Cheng-Cycle turbine

Figure 7 shows the extension of results in Fig. 4 to include a waste heat steam generator that would permit operation at higher loads. Figure 8 includes the extension of results in Fig. 5 to show the effect of the matched steam generator on exhaust temperature. The limits shown in these figures could be achieved for the Garrett IE831-800 turbine when operated in the Cheng-Cycle mode.

Concluding Remarks

In summary, the test results confirm the efficiency gains predicted from thermodynamic analysis of the Cheng Cycle when applied to the small turbine. The efficiency increases appreciably, fuel need for a given load decreases, exhaust temperature decreases and the maximum load capacity of the turbine increases markedly. Thus both the capital investment and the operating cost per unit of energy are reduced as compared with the usual Brayton-cycle mode to turbine operation. Thus the Cheng-Cycle engine simultaneously meets the need for more efficient and less polluting energy converters.

Acknowledgments

The authors appreciate the support and encourgement of the Onan Corporation in allowing them to utilize the Onan 560 Gtu Set.

References

1 Cheng, D. Y., "Parallel-Compound Dual-Fluid Heat Engine," Patent No. 3978661, Sept. 7, 1976.

2 Cheng, D. Y., "Regenerative Parallel Compound Dual-Fluid Heat Engine," Patent No. 4128994, Dec. 12, 1978.

3 Cheng, D. Y., "Regenerative Parallel Compound Dual-Fluid Heat Engine: Continuation of Patent No. 4128994 is a Separate Patent," Patent No. 4248039, Feb. 3, 1981.

4 Cheng, D. Y., "Dual-Fluid Approximation," International Power Technology internal report.

5 Chang, C. N., and Digumarthi, R., "Measurements of Low-Level No_x Emission from a Cheng Cycle Gas Turbine,"

Printed in U.S.A.