Journal of Energy Challenges
and Mechanics
http://www.nscj.co.uk/JECM/

ISSN 2056-9386
Volume 4 (2017) issue 1, article 2

Distributed energy via high-efficiency ceramic gas turbines fueled by 25-MW wind turbines in the "Roaring Forties"

由25兆瓦风力发电机组驱动之高效陶瓷燃气轮机于“咆哮西风带”所生成的分布式能源

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Accepted for publication on 24th August 2017

Abstract: **The gas turbines are based on MIT patents that use very low cycle pressure ratios (e.g., 2.5:1) facilitated by very-high-effectiveness (e.g., 97%) regenerative heat exchangers. The low-pressure ratios are produced by compressors and turbines that have low blade speeds (e.g., 250 m/s vs. 600 m/s in "regular" designs), involving low stresses (proportional to the square of the blade speed) that permit ceramics to be reliably used in the hot-gas turbines, and that have very low noise levels (turbomachinery noise being proportional to approximately the fourth power of blade speed). A power output of 300 kW has been chosen, and the cycle waste heat can be used for building heating and cooling leading to overall efficiencies (energy used and delivered divided by energy input) around 80 percent. The energy input is initially from natural gas that can be supplemented by the infusion of hydrogen produced preferably by far-offshore wind turbines in the high-wind belt south of Australia, New Zealand and the Tierra del Fuego. A new form of turbine would be very reliable at average wind speeds of 30 m/s producing compressed hydrogen from seawater that could be delivered to pipelines up to 100-km long to which floating turbines could be connected and tethered, and the fuel could be transferred to tankers at land-based ports. These wind turbines could be as much as 25-MW capacity each, and a reasonably sized wind farm in this belt could eventually supply the energy corresponding to the entire world's 2016 usage of fossil fuels**.

Keywords: **distributed energy, ceramic hot-gas turbines, high-wind turbines, intrinsic fuel production from wind turbines**

I. INTRODUCTION

This paper may be criticized for being a shameless attempt to ask for a second look at a failed concept. However, an early failure is nowadays happily regarded as potentially excellent education. The concept is one that could claim to be capable of "saving the world" (major reduction in CO2 emissions, higher electricity-generation efficiency, and a great reduction in transmission lines), and one where the weak points of the first realization have been substantially strengthened.

The original concept for distributed energy generation through small high-efficiency gas turbines was based on two MIT patents, one being for a very-high-efficiency thermodynamic cycle[1] and the other for a very-high-effectiveness regenerative heat exchanger.[2] In combination, these could result in 300-kW generators with electrical efficiencies of 50 percent. Most distributed-energy arrangements use petrol or diesel engines that have substantially lower efficiencies, shorter lives and greater noise and pollutant emissions, so that the concept had considerable promise for taking over general electricity production. Proponents of distributed generation like to point to the switch from central large computers to individual desktop or laptop computers to forecast what is possible and likely. The 300-kW generator size is appropriate for small businesses, hospitals or groups of homes (figure 1.)

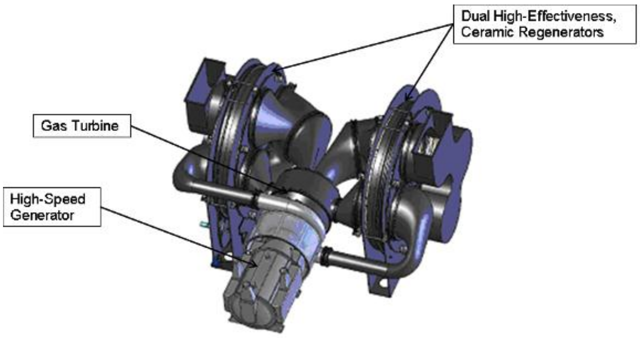


Fig.1, Wilson TurboPower 300-kW gas-turbine generator

The efficiencies of electricity “at the plug” for homes and small businesses is presently in the mid-thirties, even when the electricity is generated by 250-MW combined-cycle plants with efficiencies that may be over 60 percent. Distributed energy eliminates long cross-country transmission lines, and step-up and step-down transformers are not needed. In addition, the waste heat, 50 – 60 percent of the input energy, can be used for building heating or cooling on site. It is economic to transport waste heat only a few hundred meters, so that little of the waste heat from central plants is used, but virtually all that from distributed plants can be profitably employed. Thereby the overall energy efficiency of distributed generation can be in the seventies or eighties, and could take over electricity generation and distribution.

II. DISTRIBUTED ENERGY

2.1. THE BRAYTON (JOULE) CYCLE EMPLOYED

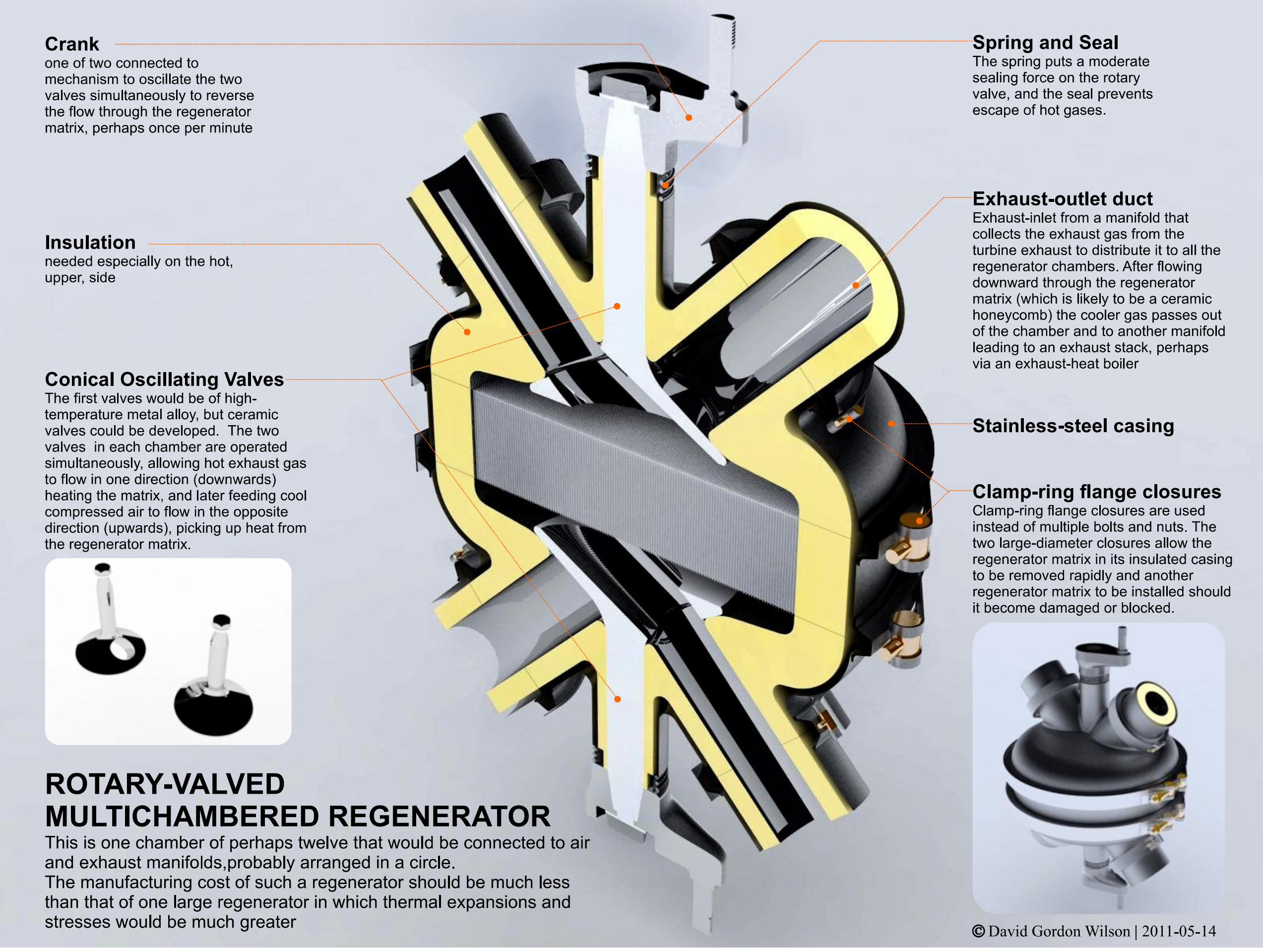
The thermodynamic cycle of the original concept was reviewed favorably by “outside” consultants (Brayton Energy, Hampton, New Hampshire) and is being retained. It has considerable advantages for distributed applications. The Brayton cycle used for aircraft and for combined-cycle gas turbines is simple, having a compressor, a combustor, and an expansion turbine. In a combined-cycle plant the compressor pressure ratio maybe thirty or forty to one, requiring expensive compressor blades and rotors running at high speeds and Mach numbers. The pressure ratio of our 300-kW compressor is 2.5:1, capable of being delivered by a small number (e.g., four) of axial-flow compressor stages running at low Mach numbers and speeds (blade speeds of about 250 m/s, versus over 600 m/s for combined-cycle plants.) The noise produced by blading is proportional to about the fourth power of blade speed, giving almost whisper quietness for the distributed-power engines. A high turbine-inlet temperature is essential for aircraft and combined-cycle turbines because it increases the thermal efficiency and reduces the turbine size simultaneously, and current values are in the region of 1650℃. The air-cooled blades are extremely expensive, and are out of consideration for the tiny turbine blades of a 300-kW engine. We are instead using ceramic blisks (combinations of blades and disks), initially in silicon carbide which were tested to run at double design speed, figure 2.

Fig. 2, Silicon Carbide turbine rotor made by Saint Gobain to Wilson TurboPower design

We would make future blisks in silicon nitride because of its much lower susceptibility to thermal-shock failure and its capability for the use of a higher turbine-inlet temperature. We are able to choose ceramics because of the very low blade speeds and consequently low centrifugal stress produced in our design. Our turbine-inlet temperature is conservatively set at 1230℃, capable of future increase in temperature and efficiency. (The lack of need for air cooling compensates somewhat for the relatively low temperature.) The three turbine stages have three identical blisks with blades shortened for the first and second stages, and a patented connection system.[3]

These small engines operate on the heat-exchanger cycle, in which the hot turbine exhaust passes through a heat exchanger that transfers heat to the compressed air leaving the axial-flow compressor, and thus reduces the gas fuel needed in the combustors. Such cycles have low optimum pressure ratios, very low for high-effectiveness heat exchangers. The effectiveness attained from our patented ceramic-honeycomb regenerators was about 0.975, far higher than the usual 0.75-0.85 for gas-turbine recuperators. However, the leakage was higher than desirable and would penalize the overall thermal efficiency of the engine. We have since patented (Ref. 4) an improved regenerator shown in figure 3 that should produce an equivalent effectiveness coupled with very low leakage.

In the original regenerator, the circular ceramic honeycomb matrix was periodically accelerated in rotation and then brought to rest so that the seals could be clamped during a short rest. In the new regenerator shown the ceramic matrix is stationary and ceramic valves periodically switch the flow



Crank
one of two connected to mechanism to oscillate the two valves simultaneously to reverse the flow through the regenerator matrix, perhaps once per minute

Insulation
needed especially on the hot, upper, side

Conical Oscillating Valves
The first valves would be of high-temperature metal alloy, but ceramic valves could be developed. The two valves in each chamber are operated simultaneously, allowing hot exhaust gas to flow in one direction (downwards) heating the matrix, and later feeding cool compressed air to flow in the opposite direction (upwards), picking up heat from the regenerator matrix.

ROTARY-VALVED MULTICHAMBERED REGENERATOR
This is one chamber of perhaps twelve that would be connected to air and exhaust manifolds,probably arranged in a circle.
The manufacturing cost of such a regenerator should be much less than that of one large regenerator in which thermal expansions and stresses would be much greater

Spring and Seal
The spring puts a moderate sealing force on the rotary valve, and the seal prevents escape of hot gases.

Exhaust-outlet duct
Exhaust-inlet from a manifold that collects the exhaust gas from the turbine exhaust to distribute it to all the regenerator chambers. After flowing downward through the regenerator matrix (which is likely to be a ceramic honeycomb) the cooler gas passes out of the chamber and to another manifold leading to an exhaust stack, perhaps via an exhaust-heat boiler

Stainless-steel casing

Clamp-ring flange closures
Clamp-ring flange closures are used instead of multiple bolts and nuts. The two large-diameter closures allow the regenerator matrix in its insulated casing to be removed rapidly and another regenerator matrix to be installed should it become damaged or blocked.

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Fig. 3, Rotary-valved Multichambered Regenerator, patent 13/481,469

direction through the matrix. The cost of these small engines should be considerably below that of the central plants and distribution systems.

2.2. GASEOUS FUELS

These distributed engines would use natural gas or other gaseous fuels initially, of which the world appears to have plenty. However, such fossil fuels, even though used at reduced flow rates, still contribute to global warming, and the use of "green" gases is needed in the long term. I am advocating the study of far-offshore wind in view of its outstanding apparent attractiveness.

In this I may be accused of bias, because my parents came from New Zealand. To the south of that country (and of Australia, South Africa and of the Tierra del Fuego) is a belt of the earth's surface uninterrupted by land or mountains, known as the Roaring Forties and Furious Fifties. Data on the winds in this belt are spotty, but there seems to be general agreement that the average wind speed is around 30 m/s, coming generally from the west. In most other off-shore wind areas, e.g., the North Sea, the average winds are less than half this value, under 12 m/s. The power produced by a wind turbine varies as the cube of the wind speed. The largest wind turbines presently available are rated at 8-MW, Therefore, it is possible that if one of these turbines were set up in this high-speed belt it could produce over 100 MW.

The off-shore wind technology is developing very rapidly at present (see magazines such as "Windpower" in addition to conference papers) and I am not sufficiently skilled or adventurous to forecast what might be possible in ten years. I will instead suggest that we would want to be cautious and conservative to start with and to specify that the first turbines installed should be rated at 25 MW, based on using considerably smaller turbines in this high-wind area than the largest that are available. I would also advocate developing a new type of horizontal-axis turbine that should require less maintenance than existing geared turbines, and indeed may be not maintained at all but simply replaced (see below).

Although turbine gears are being continually improved, gear failure is still a serious problem in wind turbines. Gearing is often desirable because the optimum peripheral speed of the rotor of an electrical generator is around 100 m/s. The tip-speed ratio (blade peripheral speed over wind speed) of a standard three-bladed turbine is 6-7. Therefore, in the usual wind-speeds averaging under 12 m/s the blade tips are approaching the optimum speeds. One could simplify the generation machinery and do without the gearbox by putting iron armatures on the blade tips and have these go through magnetic fields in stationary passages (figure 4.) For three-bladed wind turbines these would need to be in two 60-degree sectors on either side of the turbine central support.

These sectors are large, and using six-bladed turbines instead of three would reduce the spread of the stator sectors considerably smaller turbines in this high-wind area than the largest that are available. I would also advocate developing a new type of horizontal-axis turbine that should require less maintenance than existing geared turbines, and indeed may be not maintained at all but simply replaced (see below).

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These sectors are large, and using six-bladed turbines instead of three would reduce the spread of the stator sectors to only 30 degrees on either side of the central strut (figure 5.) The tip-speed ratio of a six-bladed rotor is about 3.5 so that the matching would again be pretty good.

Fig. 4, Three-blade no-gearbox wind turbine

I am further proposing (under the guidance of the MIT Technology Licensing Office) that the blading be stabilized by triangulated tensile cables (figure 5) to increase the accuracy of the fit of the blade tips to the channels.

Each turbine could produce electricity that could be brought to land directly, or could be converted to hydrogen or possibly to alcohol or other liquid fuel.

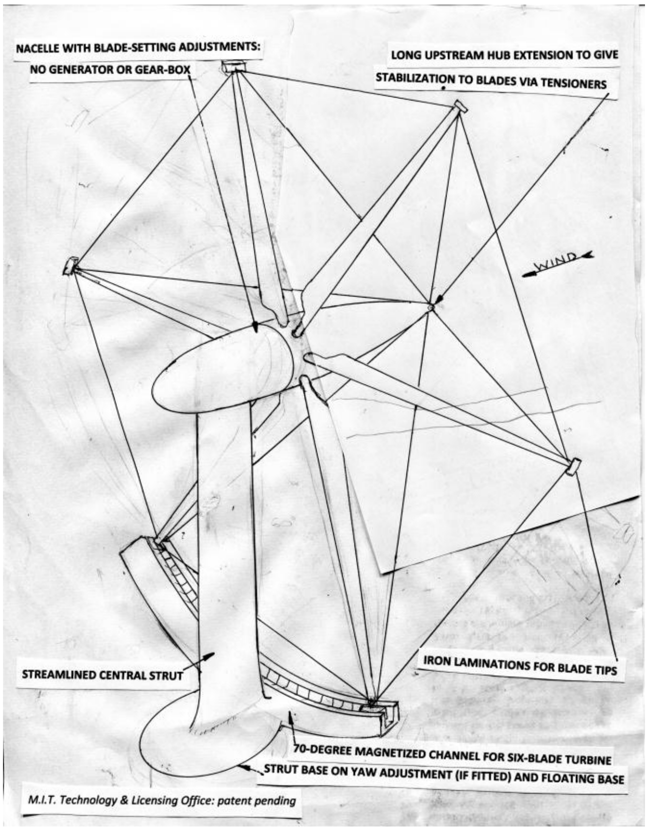

Fig. 5, Six-blade no-gearbox stabilized wind turbine

2.3. HARVESTING

The maximum economic length of a delivery conduit for electricity or hydrogen or liquid fuel from an off-shore turbine is about 100 km. We do not yet know whether the mean wind speed increases steadily as one goes south from Dunedin, NZ, or if there is a local maximum along the way, or if one reaches an economic optimum before going the full distance.

At the shore the turbines would be assembled and towed out to the selected position and erected, floating and tethered (Ref. 5) and connected to shore by the power-delivery system chosen. On-shore there would also be systems to convert the electricity to gaseous or liquid fuel and loaded on to tankers for delivery around the world. Typically, a long-distance fuel tanker uses about 2 percent of its fuel for its delivery. Others have considered shipping hydrogen, and have concluded that pure hydrogen can be injected into natural-gas pipelines with no added risks. (I would want to see this finding thoroughly checked.)

2.4. SIZE OF WIND FARM

The US consumption of energy is about 100 quads per year. The world consumption can be guessed to be roughly 400 quads per year. One quad is 10^{15} BTU, or 1.055×10^{18} joules. If the average output of the 25-MW turbines is 20 MW, the number of turbines required to supply the whole world's present usage of fossil fuels is:

$400\times1.055\times10^{18}$ / $(20\times10^{6}\times365\times24\times3600)$ = 669,000 25-MW wind turbines

This could amount to a square array of about 817 turbines on each side.

If the turbines are spaced 400 m apart, the wind farm will be about 326 km square. This is large, but if it can supply the entire world's energy while reducing the production of greenhouse gases almost to zero it seems small. In addition, there is a strong likelihood of large increases in turbine capacity being brought about from the experiences of development.

2.5. SOME OTHER ADVANTAGES

The death toll to birds and bats can be high around land or water-based wind turbines. In some places, human observers watch for eagles and falcons and can shut down the turbines if the birds come close. There are no known bird flight paths in the Roaring Forties, nor regular shipping lanes. This can be regarded as a substantial advantage, because concern over bird safety is very likely to increase.

If the wind is constantly westerly (perhaps with a deviation of plus or minus ten degrees), it might be possible to leave out the rotary pivot on the nacelle, thus reducing turbine cost and increasing reliability.

III. CONCLUDING STATEMENT

The second part of this paper, the supply of green fuel to distributed gas turbines produced by a new type and unusual location of off-shore wind turbines, is proposed as an apparently very attractive area for study. An early version has been on my energy website (LESSGOVLETSGO.org) for over ten years, apparently without producing action or comment. I would welcome feedback. It is obvious, however, that considerable prior work should be done before this concept can be seriously studied. At least a year of accurate data on wind magnitude, direction and temperature must be collected at various locations in the ''Roaring Forties." The optimum method of shipping energy from the wind turbines to shore, and then to locations around the world needs at least a preliminary decision. The "triangulated" wind turbine should be examined to choose whether to use radial blades and angled tension wires or angled blades and radial tension wires. If six blades have economic advantages over three blades should nine or ten be considered? We know that the aerodynamic efficiency decreases with an increase in the number of blades unless a ring of de-swirl stator blades is added. Should maintenance be carried out for the wind turbines, or would substitution be better? Will fixed-direction wind turbines be economically acceptable?

REFERENCES

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[2] Patent US RE37,134 E "Heat exchanger containing a component capable of discontinuous movement" Apr. 17, 2001

[3] Patent 20,130,302,163 "Method and apparatus for connecting turbine rotors", November 14, 2013

[4] Patent 13/481,469 " Rotary-valved Multichambered Regenerator"

[5] Sclavounos, P. D., Lee, S., DiPietro, J., Potenza, G., Caramuscio, P., and De Michele, G., "Floating Off-shore Wind Turbines: Tension-Leg platform and taut-leg buoy concepts supporting 3-5-MW Wind Turbines", European Wind Energy Conference, Warsaw, Poland, April 2010