SOLAR DISH ENGINE

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ABSTRACT

This paper deals with the use dish/engine systems. This paper described use Stirling cycle engines and Brayton cycle engines.

1. INTRODUCTION

Dish/engine systems convert the thermal energy in solar radiation to mechanical energy and then to electrical energy in much the same way that conventional power plants convert thermal energy from combustion of a fossil fuel to electricity. As indicated in Fig.1, dish/engine systems use a mirror array to reflect and concentrate incoming direct normal insolation to a receiver, in order to achieve the temperatures required to efficiently convert heat to work. This requires that the dish track the sun in two axes. The concentrated solar radiation is absorbed by the receiver and transferred to an engine.

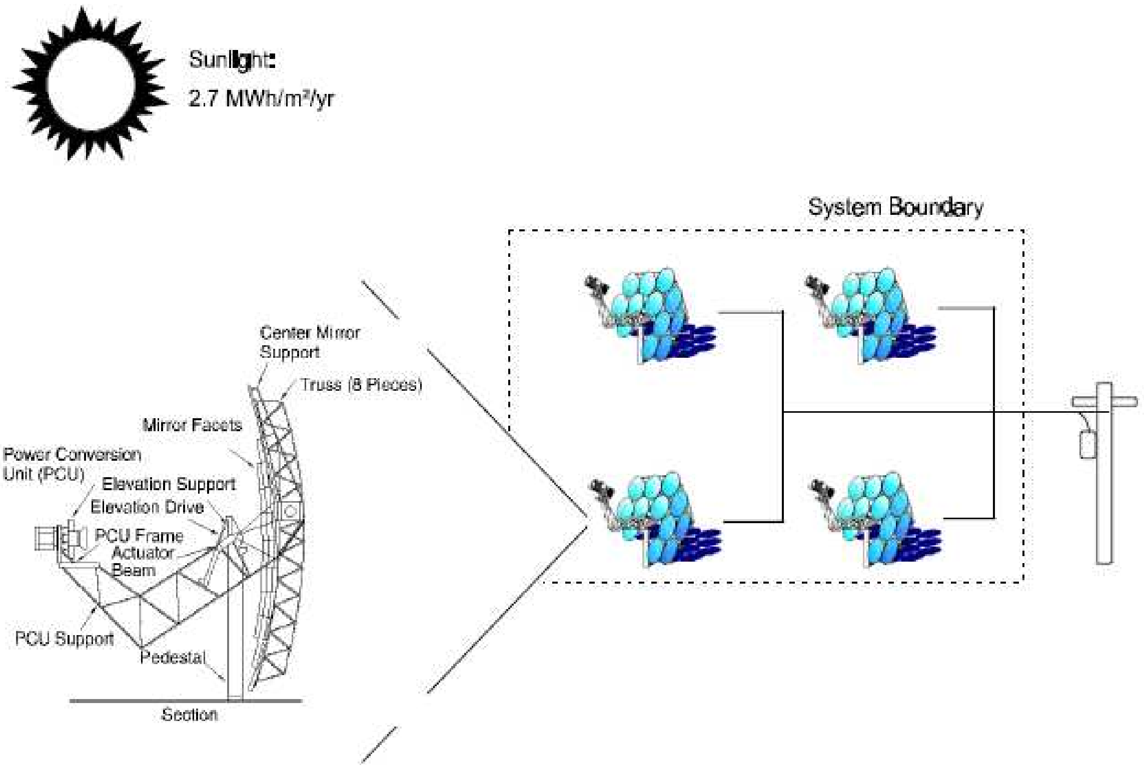

Fig.1. Dish/engine system schematic. The combination of four 25 kW_e units shown here is representative of a village power application [1].

Dish/engine systems are characterized by high efficiency, modularity, autonomous operation, and an inherent hybrid capability (the ability to operate on either solar energy or a fossil fuel, or both). Of all solar technologies, dish/engine systems have demonstrated the highest solar-to-electric conversion efficiency (29.4%)[1], and therefore have the potential to become one of the least expensive sources of renewable energy. The modularity of dish/engine systems allows them to be deployed individually for remote applications, or grouped together for small-grid (village power) or end-of-line utility applications. Dish/engine systems can also be hybridized with a fossil fuel to provide dispatchable power. This technology is in the engineering development stage and technical challenges remain concerning the solar components and the commercial availability of a solarizable engine. The following describes the components of dish/engine systems, history, and current activities.

2. ENGINES

The engine in a dish/engine system converts heat to mechanical power in a manner similar to conventional engines, that is by compressing a working fluid when it is cold, heating the compressed working fluid, and then expanding it through a turbine or with a piston to produce work. The mechanical power is converted to electrical power by an electric generator or alternator. A number of thermodynamic cycles and working fluids have been considered for dish/engine systems. These include Rankine cycles, using water or an organic working fluid; Brayton, both open and closed cycles; and Stirling cycles. Other, more exotic thermodynamic cycles and variations on the above cycles have also been considered. The heat engines that are generally favored use the Stirling and open Brayton (gas turbine) cycles. The use of conventional automotive Otto and Diesel engine cycles is not feasible because of the difficulties in integrating them with concentrated solar energy. Heat can also be supplied by a supplemental gas burner to allow operation during cloudy weather and at night. Electrical output in the current dish/engine prototypes is about 25 Kw_e for dish/Stirling systems and about 30 kW_e for the Brayton systems under consideration. Smaller 5 to 10 kW_e dish/Stirling systems have also been demonstrated.

1) Stirling Cycle:

Stirling cycle engines used in solar dish/Stirling systems are high-temperature, high-pressure externally heated engines that use a hydrogen or helium working gas. Working gas temperatures of over 700°C (1292ºF) and as high as 20 MPa are used in modern high-performance Stirling engines. In the Stirling cycle, the working gas is alternately heated and cooled by constant-temperature and constant-volume processes. Stirling engines usually incorporate an efficiency-enhancing regenerator that captures heat during constant-volume cooling and replaces it when the gas is heated at constant volume. Fig.2 shows the four basic processes of a Stirling cycle engine. There are a number of mechanical configurations that implement these constant-temperature and constant-volume processes. Most involve the use of pistons and cylinders. Some use a displacer (a piston that displaces the working gas without changing its volume) to shuttle the working gas back and forth from the hot region to the cold region of the engine. For most engine designs, power is extracted kinematically by a rotating crankshaft. An exception is the free-piston configuration, where the pistons are not constrained by crankshafts or other mechanisms. They bounce back and forth on springs and the power is extracted from the power piston by a linear alternator or pump. A number of excellent references are available that describe the principles of Stirling machines. The best of the Stirling engines achieve thermal-to-electric conversion efficiencies of about 40% [2-4]. Stirling engines are a leading candidate for dish/engine systems because their external heating makes them adaptable to concentrated solar flux and because of their high efficiency.

Currently, the contending Stirling engines for dish/engine systems include the SOLO 161 11-kW_e kinematic Stirling engine, the Kockums (previously United Stirling) 4-95 25-kW_e kinematic Stirling engine, and the Stirling Thermal Motors STM 4-120 25-kW_e kinematic Stirling engine. (At present, no free-piston Stirling engines are being developed for dish/engine applications.) All of the kinematic Stirling engines under consideration for solar applications are being built for other applications. Successful commercialization of any of these engines will eliminate a major barrier to the introduction of dish/engine technology. The primary application of the SOLO 161 is for cogeneration in Germany; Kockums is developing a larger version of the 4-95 for submarine propulsion for the Swedish navy; and the STM4-120 is being developed with General Motors for the DOE Partnership for the Next Generation (Hybrid) Vehicle Program[2-4].

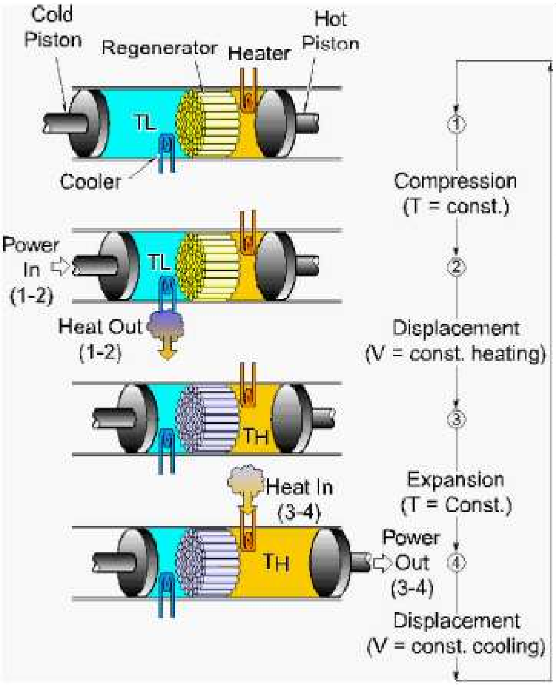

Fig.2. Schematic showing the principle of operation of a Stirling engine [2-4].

2) Brayton Cycle:

The Brayton engine, also called the jet engine, combustion turbine, or gas turbine, is an internal combustion engine which produces power by the controlled burning of fuel. In the Brayton engine, like in Otto and Diesel cycle engines, air is compressed, fuel is added, and the mixture is burned. In a dish/Brayton system, solar heat is used to replace (or supplement) the fuel. The resulting hot gas expands rapidly and is used to produce power. In the gas turbine, the burning is continuous and the expanding gas is used to turn a turbine and alternator.

As in the Stirling engine, recuperation of waste heat is a key to achieving high efficiency. Therefore, waste heat exhausted from the turbine is used to preheat air from the compressor. A schematic of a single-shaft, solarized, recuperated Brayton engine is shown in Fig.3. The recuperated gas turbine engines that are candidates for solarization have pressure ratios of approximately 2.5, and turbine inlet temperatures of about 850°C (1,562°F). Predicted thermal-to-electric efficiencies of Brayton engines for dish/Brayton applications are over 30% [5,6].

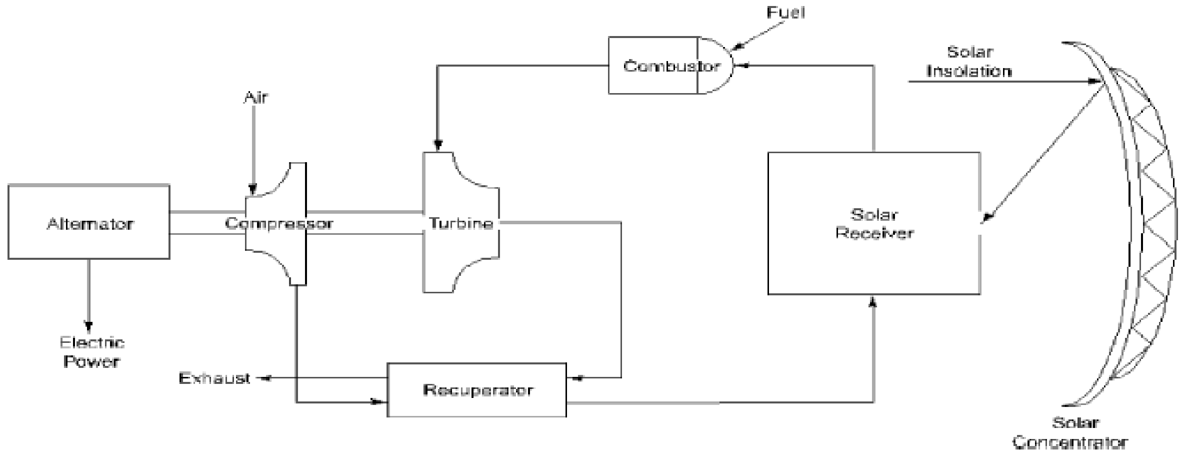

Fig.3. Schematic of a Dish/Brayton system [5,6].

The commercialization of similar turbo-machinery for various applications by Allied Signal, Williams International, Capstone Turbines Corp., Northern Research and Engineering Company (NREC), and others may create an opportunity for dish/Brayton system developers.

3. TECHLONOGY

1) 1997 Technology:

The base-year technology (1997) is represented by the 25 kW_e dish-Stirling system developed by McDonnell Douglas (MDA) in the mid 1980s. Similar cost estimates have been predicted for the Science Applications International Corporation (SAIC) system with the STM 4-120 Stirling engine [7]. Southern California Edison Company operated a MDA system on a daily basis from 1986 through 1988. During its last year of operation, it achieved an annual efficiency of 12% despite significant unavailability caused by spare part delivery delays. This annual efficiency is better than what has been achieved by all other solar electric systems, including photovoltaics, solar thermal troughs, and power towers, operating anywhere in the world [8,9]. The base-year peak and daily performance of near-term technology are assumed to be that of the MDA systems. System costs assume construction of eight units. Operation and maintenance (O&M) costs are of the prototype demonstration and accordingly reflect the problems experienced.

2) 2000 Technology:

Near-term systems (2000) are expected to achieve significant availability improvements resulting in an annual efficiency of 23%. The MDA system consistently achieved daily solar efficiencies in excess of 23% when it was operational. The low availability achieved with the base-year technology was primarily caused by delays in receiving spare parts and by the lack of a dedicated O&M staff. A 23% annual efficiency is, therefore, a reasonable expectation, assuming Stirling engines are commercialized for other applications, and spare parts and a dedicated staff are available. In addition, near term technologies should see a modest reduction in the cost of the dish concentrator simply as a result of the benefits of an additional design iteration. Prototypes for these near-term technologies were first demonstrated in 1985 by McDonnell Douglas and United Stirling. Similar operational behavior was demonstrated in 1995 by SAIC and STM, although for a shorter test period and a lower system efficiency. O&M costs reflect improvements in reliability expected with the introduction of a commercial engine. Production of 100 modules is assumed. At this production rate, component costs are high, resulting in installed costs of nearly \$5,700/kW_e.

3) 2005 Technology:

Performance for 2005 is largely based on one of the solarizable engines being commercialized for a non-solar application (e.g., GM’s introduction of the STM 4-120 Stirling engine for use in hybrid vehicles). Use of a production level engine will have a significant impact on engine cost as well as overall system cost. This milestone will help trigger a fledgling dish/engine industry. A production rate of 2,000 modules per year is assumed. Achieving a high production rate is key to reducing component costs, especially for the solar concentrator.

4) 2010 Technology:

Performance for years 2010 and beyond is based on the introduction of the heat-pipe solar receiver. Heat-pipe solar receiver development is currently being supported by SunLab in collaboration with industrial partners. The use of a heat-pipe receiver has already demonstrated performance improvements of well over 10% for the STM 4-120 compared to a direct-illumination receiver [1]. While additional improvements in mirror, receiver, and/or engine technology are not unreasonable expectations, they have not been included. This is, therefore, a conservative scenario. A production rate of 30,000 modules per year is assumed.

By 2010 dish/engine technology is assumed to be approaching maturity. A typical plant may include several hundred to over a thousand systems. It is envisioned that a city located in the U.S. Southwest would have several 1 to 50 MW_e installations located primarily in its suburbs. A central distribution and support facility could service many installations. In the table, a typical plant is assumed to be 30 MW_e.

4) 2020 - 2030 Technology:

Production levels for 2020 and 2030 are 50,000 and 60,000 modules per year, respectively. No major advances beyond the introduction of heat pipes in the 2010 time frame are assumed for 2020-2030. However, evolutionary improvements in mirror, receiver, and/or engine designs have been assumed. This is a reasonable assumption for a $2 billion/year, dish/engine industry, especially one leveraged by a larger automotive industry. The system costs are therefore 20 to 25% less than projected by MDA and SAIC at the assumed production levels. The MDA and SAIC estimates are for their current designs and do not include the benefits of a heat-pipe receiver. In addition, the MDA engine costs are for an engine that is being manufactured primarily for solar applications. Advanced concepts (e.g., volumetric Stirling receivers) and/or materials, which could improve annual efficiency by an additional 10%, have not been included in the cost projections. With these improvements installed costs of less than $1,000/kW$_e$ are not unrealistic.

3. CONCLUSIONS

Dish/Engine Systems use an array of mirrors, arranged in the shape of a dish, to concentrate sunlight onto a receiver placed at the focal point of the dish. The heat produced by these systems is transferred to a heat engine which converts the heat into mechanical energy. This energy then drives a generator to produce electricity.

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