Development and performance analysis of a hybrid solar gas turbine

Lars-Uno Axelsson and Darsini Kathirgamanathan, OPRA Turbines, the Netherlands

With the increased amount of non-controllable renewables feeding the electric grid, such as wind and solar energy, it is difficult to maintain the stability of the grid. Thermal solar plants can address and solve this challenge by operating them in combination with a conventional prime mover. In hybrid solar gas turbine plants the environmental benefits of the solar energy are combined with the operational benefits of the gas turbines. In the hybrid solar gas turbine the compressor air is heated by the solar energy before it enters the combustion chambers. This means that the conventional fossil fuel can be (partly) substituted by the solar energy; hence, the fuel consumption and pollutant emissions will be reduced. A challenge with conventional thermal solar plants is the varying availability of the solar energy. However, the hybrid solar gas turbine solution will ensure a continuous and stable power generation as the gas turbine can operate on a conventional fossil fuel when there is no or little solar energy available.

OPRA Turbines is involved in an R&D project with the aim to integrate a gas turbine, based on the OP16 gas turbine product line, into an existing solar plant. The OP16 is an all-radial gas turbine and the simple and robust configuration makes it suitable for conversion to a hybrid solar gas turbine. This paper will start with a general description of the benefits and challenges of hybrid solar plants. Next, the benefits of utilizing a gas turbine as the prime mover in the solar plant will be discussed followed by a description of the OP16 hybrid solar gas turbine concept. The paper will be concluded with a presentation of the performance data for the hybrid solar gas turbine.

1. Introduction

The demand for more environmentally friendly power generation has increased the share of renewables in the energy mix. However, the renewable energy sources such as wind and solar based plants are strongly depending on the weather conditions. The large variation in the availability of these renewable energy sources makes it challenging to maintain the stability of the electric grids. In addition, the rapid transient behavior of the renewables when the weather conditions changes requires alternative energy sources to cover for the loss of wind and solar energy.

Today, two technologies dominate the solar power market: Solar photovoltaics and solar thermal plants. The former technology provides the lowest cost of electricity. However, its electrical output is highly unreliable and variable as it depends on the instant solar power. The solar thermal plants, on the other hand, have the possibility to be combined with other power generation units (hybridization) and storage capabilities. By employing hybrid solar thermal plants, the consumer load demand can easily be met.

The main drawback of the thermal solar plants is the relatively high cost of the electricity produced from these plants. However, several areas can be addressed in order to reduce the cost of the thermal solar plants. These efforts include reducing the cost of the individual components and reducing the auxiliary power consumption. The latter will boost the overall plant efficiency. Another promising alternative is to evaluate and design new plants based on more efficient thermodynamic cycles. Today, these plants typically utilize Rankine cycles, i.e. low-temperature steam turbine cycles. Besides having a relatively low electric efficiency the steam turbines require a high amount of water, which might not be available in the locations where the solar thermal plant is situated.

By combining the solar thermal plant with a gas turbine, instead of a steam turbine, the above issues will be addressed: Higher electric efficiency, lower water consumption, higher flexibility and the possibility to follow the load demand.

In order to demonstrate this concept, a research project employing a hybrid solar gas turbine has been initiated by CNRS. This project is developed by CNRS/PROMES and it is co-funded by the European Union through the FEDER program. It is implemented on the Themis site with support of the Region Languedoc-Roussillon and Conseil General des Pyrenees-Orientales (local public authorities). The other private and institutional partners of this project are EDF and ADEME. As part of this project, OPRA Turbines (the Netherlands) has been sub-contracted to engineer and design a gas turbine, based on the OP16 gas turbine, which can be integrated into the solar thermal power plant. This paper will discuss the hybrid solar gas turbine concept and the estimated overall performance figures.

2. Hybrid solar gas turbine plants

A typical hybrid solar gas turbine plant consists of several components (Figure 1). The main components are the solar collector, solar receiver and the prime mover. The solar collector can be of different types. The two common types that focuses the sun rays into a single point are the heliostats and dish type collectors. However, the dish type is generally only applicable for small-scale applications.

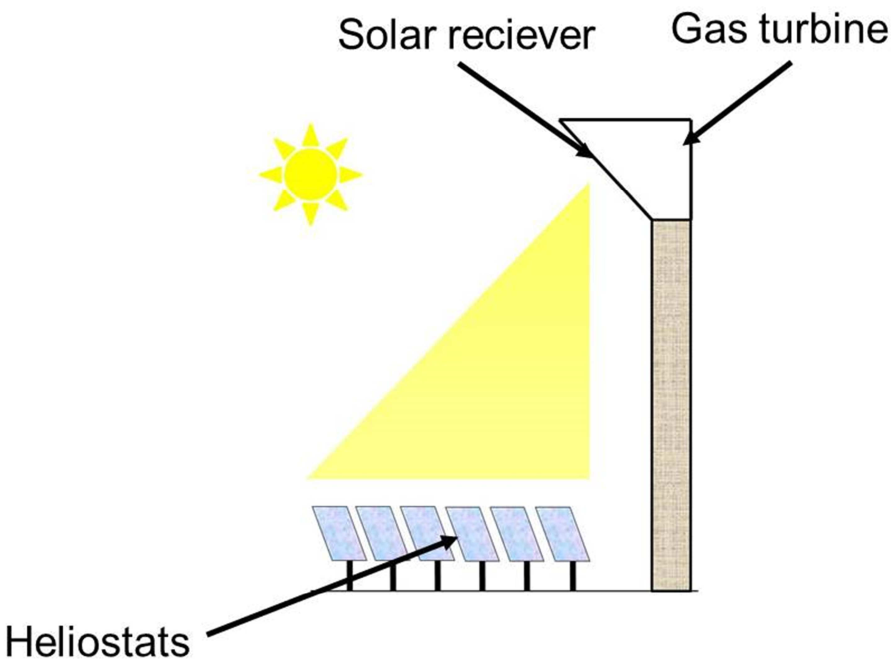

Figure 1. Typical hybrid solar gas turbine plant.

The concentrated solar power is collected in a receiver. For a field of heliostats the solar power is concentrated in a tower where the receiver is located. The prime mover has typically been steam turbines but given the drawbacks presented in previous chapter gas turbines are a more viable technology. Gas turbines are a well-proven technology and its ideal cycle is described by the ideal Brayton cycle (Figure 2). Air is sucked in by the compressor which is compressing the air (Step 1-2). Fuel is injected in the combustion chamber (step 2-3) and the heat released during the combustion increases the temperature of the fuel/air mixture. The high pressure, high temperature gas is expanded through the turbine (step 3-4) before it is exhausted to the atmosphere. The expansion in the turbine provides the work. Part of this work is used to drive the compressor (directly coupled) and the remaining portion of the produced energy is the useful power. The gas turbine shaft is coupled to a generator to transfer the mechanical power to electrical power.

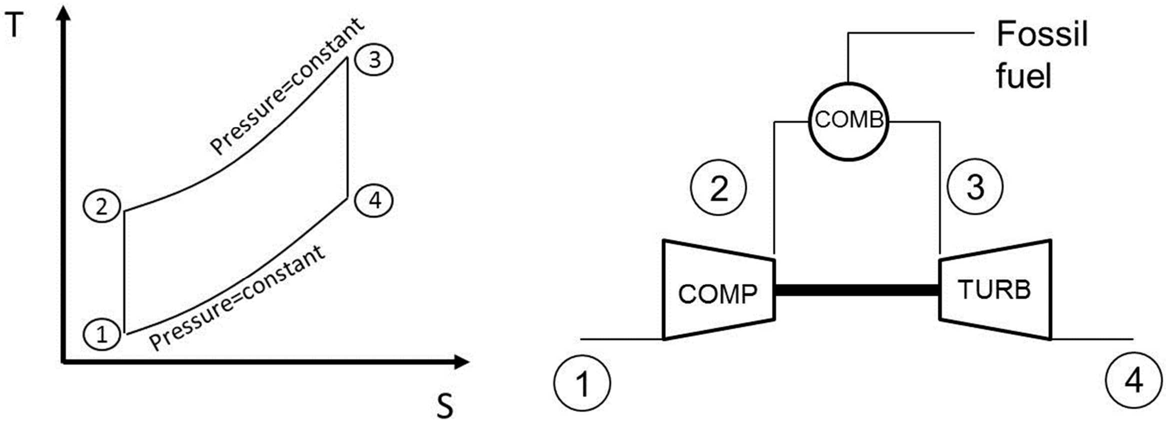

Figure 2. The ideal Brayton cycle (left).

In the hybrid solar gas turbine plant, the compressed air after the compressor is heated by the energy from the sun in a heat exchange process. The heated air is then introduced into the combustion chamber. Since it is now heated, no or only a small amount of fuel is needed to reach the correct combustor outlet temperature. This means that less fuel is needed for a given power; hence, the specific fuel consumption (SFC) reduces. As can be understand, a key factor in order to reduce the SFC is to develop solar receivers to handle as high temperatures as possible.

A main advantage of the (smaller) gas turbines is their ability to rapidly handle load variations. This can be utilized when operating them in a hybrid power plant. When the weather conditions changes and/or the sun light is decreasing the conventional fossil fuel will increase to compensate for the lower solar energy. In this case the plant can provide the same amount of power continuously even during the night and during bad weather. This is a key factor to maintain the stability of the electric grid.

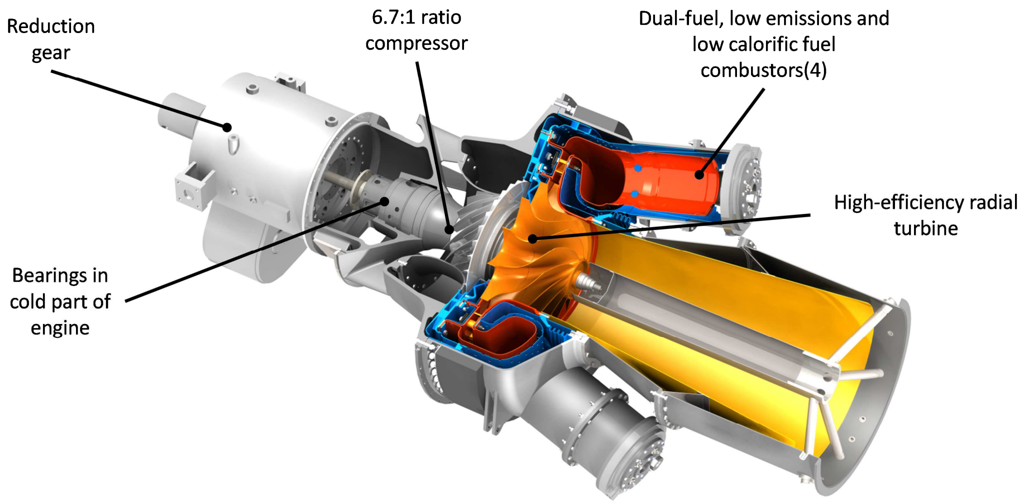

Figure 3. The OP16 gas turbine.

3. Development of the hybrid solar gas turbine

As part of the hybrid solar gas turbine plant project developed by CNRS/PROMES, OPRA Turbines (the Netherlands), has been contracted to develop the gas turbine for the solar thermal plant. This gas turbine is based on the OP16 gas turbine (Figure 3). The OP16 gas turbine is a single-shaft all-radial gas turbine for industrial, commercial, marine and oil & gas applications. Since its market introduction in 2005 many generator sets based on the OP16 gas turbine have been delivered worldwide and the fleet has accumulated about 2 million operating hours. The OP16 gas turbine features a single stage centrifugal compressor with a nominal pressure ratio of 6.7:1. The moderate pressure ratio reduces the need for gas compression prior to introducing the fuel into the gas turbine. The radial turbine wheel, which is mounted back-to back with the compressor, has been aerodynamically optimized to achieve a high efficiency. The compact compressor/turbine configuration permits the use of an overhung rotor assembly in which the bearings are located on the cold side only ensuring a long bearing life time and virtually zero lube oil consumption.

The simplicity of the OP16 gas turbine is well-suited for operation in a hybrid solar gas turbine plant, since it will provide the reliability needed to prove this concept. In order to integrate the gas turbine to the solar thermal plant, certain parts need to be modified.

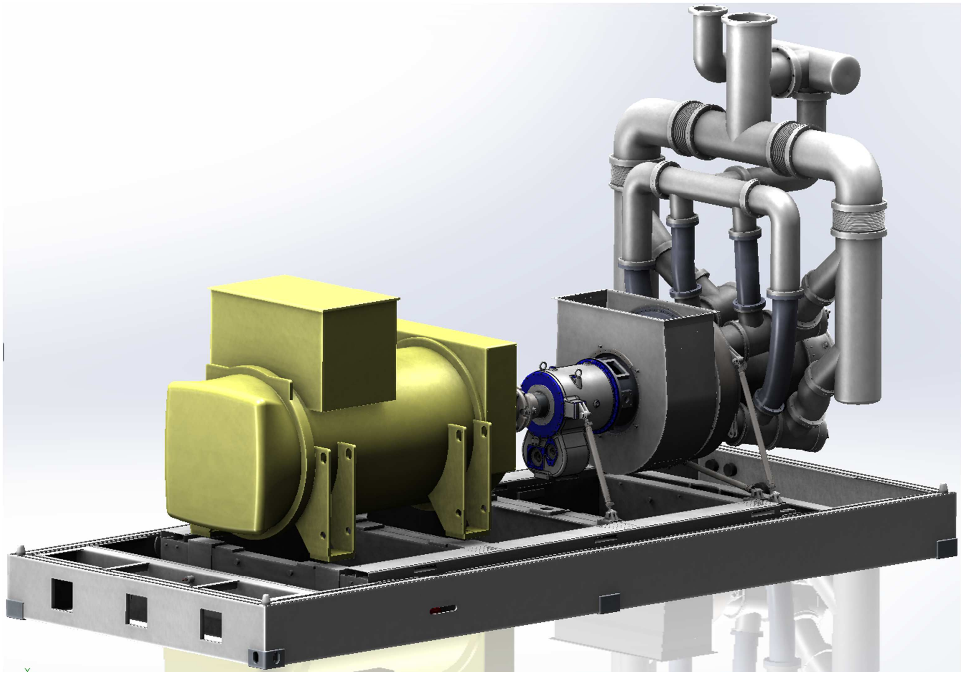

Figure 4. OP16 hybrid solar gas turbine concept.

The main modifications include:

- Combustion chambers enabling the operation on conventional fossil fuel with varying degree of solar receiver outlet temperature
- Provisions to take the (cold) compressor air out from the gas turbine and guide the hot air back to the combustors
- Control system that can handle safe and reliable operation for all operating conditions

The hybrid solar gas turbine concept mounted on the OP16 standard skid is shown in Figure 4. One can see the additional piping required to guide the air to and from the solar receiver. Each of the four combustion chambers has one outlet and one inlet. By taking the air out from each combustion chamber the core of the engine can remain the same. The piping diameter has been selected in order to minimize the pressure loss through the system. Although the addition of the piping system seems large, it still fits within the footprint of the standard skid of the gen-set. The piping system is supported by a support structure attached to the skid (not shown). The piping system has only two interfaces towards the solar receiver (one inlet and one outlet) to minimize the complexity.

4. Performance evaluation of the hybrid solar gas turbine

To evaluate the performance of the hybrid solar gas turbine, cycle simulations have been performed. The results are summarized in Table 1. Four different cases are analyzed. Case 1 is the conventional gas turbine without the modifications required for the hybridization. Case 2-4 are the performance data for the modified solar gas turbine. Case 2 represents the case where there is no solar power available. The difference between Case 1 and Case 2 are the additional pressure loss caused by the piping and valves to and from the solar receiver. Case 3 corresponds to a medium solar input and Case 4 corresponds to a high solar input. For all the simulations diesel No. 2 is used as the fossil fuel and it is considered that the unit is installed at sea level.

Table 1. Performance data for the hybrid solar gas turbine.

Parameters	**Unit**	**Value**			
Operating conditions		*Case 1*	*Case 2*	*Case 3*	*Case 4*
Inlet pressure	[Pa]	101325	101325	101325	101325
Inlet temperature	[^{0}C]	15	15	15	15
Relative humidity	[%]	60	60	60	60
Inlet pressure loss	[Pa]	750	750	750	750
Exhaust pressure loss	[Pa]	1000	1000	1000	1000
Combustor inlet temperature	[K]	548	551	776	1073
Results					
Mass flow	[kg/s]	8.7	8.6	8.1	8.1
Fuel flow	[g/s]	175	171	116	50
Exhaust temperature	[K]	865	866	875	874
Exhaust mass flow	[kg/s]	8.9	8.8	8.3	8.1
Electric power	[kW]	1830	1762	1529	1438
Specific fuel consumption	[g/kWh]	344	349	273	125
Solar share	[%]	0	0	27	66

One can see that the absolute power decreases as the solar input increases. There are several reasons for this. When the solar input increases the combustor inlet temperature increases; hence, the velocity through the combustor increases and therefore the pressure loss increases. The increased combustor pressure loss leads to a lower expansion ratio across the turbine and therefore the power produced is lowered. Another aspect causing the power reduction is the reduced mass flow through the turbine as the fuel flow decreases. As the solar input increases the solar share increases naturally. The solar share is defined as the heat input from the solar energy divided by the total heat input of the cycle; i.e. the combined solar heat and combustion heat. Although the absolute power decrease the SFC decreases significantly since the fuel flow decreases. For the case with a high solar input the SFC has decreased by 64%, significantly reducing the carbon footprint.

5. Conclusions

With the increased amount of non-controllable renewables feeding the electric grid, such as wind and solar energy, it is difficult to maintain the stability of the grid. Solar thermal plants can address this challenge by operating them in combination with a conventional prime mover. These, so called hybrid power plants, are relatively costly and consume a significant amount of water as they traditionally utilize steam turbines for power generation. However, by utilizing gas turbines instead the efficiency can be increased and therefore the overall cost for the electricity will be decreased. Furthermore, the gas turbines do not require water for its operation and can easily handle the rapid transients caused by the changing weather conditions.

As part of a project developed by CNRS/PROMES, OPRA Turbines is developing a gas turbine suitable for integration into an existing solar thermal plant. This hybrid solar gas turbine is based on the OP16 product line. The main modifications are related to the combustion chamber and a system for taking the air in and out from the receiver. In addition, the control system needs to be modified in order to be able to handle the varying combustor inlet temperature.

The performance calculations show that a significant reduction in SFC can be achieved. For a high solar input, more than 60% reduction in SFC can be achieved.

Acknowledgements

This project is developed by CNRS/PROMES and it is co-funded by the European Union through the FEDER program. It is implemented on the Themis site with support of the Region Languedoc-Roussillon and Conseil General des Pyrenees-Orientales (local public authorities). The other private and institutional partners of this project are EDF and ADEME.