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Thermodynamic modeling of solarized microturbine for combined heat and power applications

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HIGHLIGHTS

- Introduced a thermodynamic model for a 100 kWe/165 kWt solarized microturbine.
- Electric output of thermodynamic model is within 1.6% of the as-built system.
- Fuel use reduced by 26.0% verse traditional microturbine at maximum power output.
- Annual operating time is 59.8% fuel only, 12.4% hybrid, and 27.8% solar only modes.
- Electrical efficiency most sensitive to ambient air temperature.

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ABSTRACT

Combined heat and power (CHP) plants utilize exhaust heat from thermal-based power generators to increase system efficiency beyond electrical efficiency alone. Many existing CHP systems use fossil-fueled generators to create electrical power for retail sale or on-site industrial or commercial uses. This study develops, validates, and exercises a quasi-steady state thermodynamic model of a 100 kWe/165 kWt rated microturbine that has been coupled with a concentrating solar power (CSP) tower to offset natural gas consumption. Exhaust heat is rejected at approximately 270 °C for CHP applications. Governing equations developed for eight components incorporate manufacturer data and empirical data to describe system-level operation with respect to intraday variation in the solar resource. Model validation at ISO conditions shows electric output of the simulated system is within 1.6% of the as-built system. Simulation results of the complete solarized system gave 31.5% electrical efficiency, 83.2% system efficiency, 99.5 kWe electrical power, and 163.5 kWt thermal power at nominal operating conditions for a DNI of 515 W/m^2. The thermodynamic model is exercised under rated electrical load (base loading) and variable electrical load (load following) conditions with performance measured on 13 operating characteristics. Sensitivity analyses evaluate changes in performance with respect to operating variables (e.g., turbine inlet temperature) and environmental variables (e.g., elevation). Results show that a CSP plant with solarized microturbine can meet target performance specifications of a non-solarized microturbine (pure natural gas). Annual time series simulations completed for Phoenix, Arizona, USA indicate a solarized microturbine can reduce natural gas use by 26.0% and 28.4% when supplying rated power and variable power output, respectively. Annual operating time of the solarized microturbine at rated capacity included 59.8% fuel only, 12.4% hybrid, and 27.8% solar only modes for the selected study location.

1. Introduction

Combined heat and power (CHP) plants recover more energy than conventional turbomachinery that provides electric power only [1]. Producing heat and electrical power independently yields a combined first-law efficiency of up to 45% [2], whereas producing heat and power in a combined process can yield first-law efficiencies of up to 80–90% [3,4]. The increase in system efficiency occurs from the recovery of turbine exhaust heat that traditional power plants may not fully exploit [5]. Recovered energy improves CHP plant economics in

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both small-scale and large-scale applications [6]. Today, over 80% of the total global CHP capacity is used for commercial and industrial applications such as food processing, pulp and paper, chemical, metals refining, and oil refining sectors [7]. Medium-sized CHP systems (larger than 1 MWe and smaller than 10 MWe) are often used by industries that require a substantial amount of high quality thermal energy to complement electrical power requirements [7]. Such systems are generally site-specific in design. Smaller CHP systems (between 1 kWe and 1 MWe) can be pre-packed and configured for use in hospitals, hotels, and agro-processing facilities that have lower thermal requirements for uses such as hot water and low-temperature steam [7].

CHP designs have advanced rapidly since the first unit was installed at Thomas Edison's Pearl Street Station in 1882 to provide electricity and steam in New York City, USA [8,9]. Current CHP systems may use reciprocating engines, steam turbines, gas combustion turbines, and microturbines to produce various forms of energy output such as electricity, direct mechanical drive, steam, hot water, process heat, cooling, and/or dehumidification [10]. Microturbine CHP systems are common in commercial applications that require a minimal amount of technical work to install and operate. Microturbines typically have higher electrical efficiencies when compared to traditional gas turbines of the same power rating because of the use of a recuperation Brayton cycle rather than a classical Brayton cycle in the microturbine [11]. Microturbines also provide low emission, reliable, and quick-start power [12].

Natural gas is the most common energy source for CHP systems. Some CHP systems use renewable sources of energy to reduce environmental impact and improve long-term financials. Examples include geothermal, concentrating solar power (CSP), biomass [13], and biofuels [14–17]. Growing interest in the use of CSP heat to displace natural gas combustion in CHP applications has resulted in novel research and literature for gas turbines in the MW scale [18,19], while research in small-scale solarized CHP systems have focused on economics, receiver design and experimentation, and concentrating dish applications [20–22]. Additional study including system-level thermodynamic modeling and balance of plant analysis can further explore the potential of such systems in real operational scenarios. Experimental data from a prototype 100 kWe/165 kWt hybrid solar system [23] and a steady-state thermodynamic model developed here are used for simulated performance evaluation and sensitivity analyses with the following contributions:

- A complete quasi-steady state thermodynamic model is presented for a new class of a solarized CHP systems with a microturbine generator. Governing equations are developed for eight components that describe system-level operation with respect to intraday variation in solar resource.
- Intraday simulations are used to understand electrical and thermal power production under varying solar conditions and changing modes of operation.
- Simulated performance is completed using hourly solar radiation data for Phoenix, Arizona, USA under rated load and variable load conditions with performance measured and compared on fuel consumption, solar energy input, system efficiency, excess solar power from heliostats, and other metrics.
- Sensitivity analyses are used to explore system performance with respect to changes in operating variables (e.g., electrical power demand) and environmental variables (e.g., ambient air temperature) to both validate and compare the model against existing gas turbine thermodynamic models and manufacturer data.
- The validated solarized CHP model can be used with site data from around world to examine the technology's potential in new locations.

2. Thermodynamic model development

A quasi steady-state thermodynamic model was developed to evaluate the feasibility, operational characteristics, and performance of a fossil fueled microturbine hybridized to use solar energy. Comparable steady state and dynamic models of the Turbec T100 microturbine developed in [24,25] are extended here to encompass the full solarized CHP system. Transient characteristics during system start-up and rapid load variation are left for a separate study of component wear and system control optimization [26,27].

Fig. 1. Pilot plant CSP system with solarized CHP microturbine developed by AORA Solar Ltd [34].

Related studies have evaluated microturbine modifications to use biofuels and other low caloric fuels [28–31]. Further work investigated the effect of humid air injection on system performance and efficiency of the Turbec T100 system [32,33]. Each study used direct combustion as the only heat source and no published literature has developed a solarized version of the microturbine to offset the use of gaseous fuels as presented here. A physical system prototyped by AORA Solar Ltd. [34] complements these thermodynamic analyses and provides measured data for comparison and model validation (see Fig. 1). AORA Solar Ltd. [34] provided data specific to the state point temperatures, state point pressures, component thermal losses, component pressure losses, and operational characteristics (e.g., solar resource cut-in value and minimum fuel ratio).

The solarized microturbine CSP system in Fig. 2 has eight components: compressor, turbine, combustion chamber, recuperator, generator, heat recovery, solar receiver, and heliostat field. Numbered stream flows for air, fuel, and combustion gases are also shown. All components are in the CSP tower except for the heliostat field.

The system has three operating modes: fuel only, hybrid, and solar only. Pressure drops and thermal losses throughout the system vary with operating mode. Manufacturer data and empirical data express pressure drops across the recuperator, solar receiver, combustion chamber, and turbine as a function of operating mode and system state variables. Thermal and pressure losses in the solar receiver and combustion chamber are also expressed as a function of operating mode and system state variables. Air mass flow rate was assumed to be constant throughout all components of the microturbine given the mass of fuel added through the combustor was less than 1% of the mass of air under ISO conditions.

Thermodynamic models for each component were developed using a combination of first principles, manufacturer data, secondary data from other published studies, and empirical data. The equation set of basic and advanced thermodynamic relationships provides a complete systems-level model used to explore operational behavior and equate performance characteristics of the novel microturbine and CSP system configuration. Governing equations were written in Python. Air property data in CoolProp® was used as an approximation for combustion gases [35].