

STUDY OF A SOLID OXIDE FUEL CELL COMBUSTOR WITH A GAS TURBINE ENGINE

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ABSTRACT

Fuel cell technology has improved dramatically in recent years, and it is now a viable source of clean energy for a wide range of technical applications. Currently, stationary power production is the most common use for fuel cell technology. For mobility platforms, such as unmanned aerial vehicles, there is very little information available. With the rising usage of unmanned aerial vehicles for national security and surveillance, a more efficient, longer-lasting power supply is required to sustain the higher electrical loads aboard. Others have demonstrated that fuel cell gas turbine hybrid systems can achieve greater system efficiencies when operating at full power. In comparison to typical heat-based systems, the integration of a solid oxide fuel cell combustor with a gas turbine engine has the potential to greatly boost system efficiency in off design circumstances and have a greater energy density. As a result, bigger onboard electrical loads and longer mission durations are possible. The bulk of an unmanned air vehicle's mission time is spent loitering and operating at part load. Increasing component load efficiency extends mission duration while lowering operating expenses. When compared to traditional heat-based propulsion systems, these hybrid systems may have less power degradation at greater altitudes. The goal of this paper is to examine the performance of a solid oxide fuel cell combustor hybrid gas turbine power system at various altitudes under design and off-design operating circumstances. To examine the performance of such a system, a system-level MATLAB/Simulink model was constructed. The hybrid propulsion system was conceptualised as a commercially accessible gas turbine engine combined with an anode-supported solid oxide fuel cell for remote control aircraft. The system's design point operation was for maximum power at sea level. A steady-state component load performance investigation was carried out for loads ranging from 10% to 100% design load at altitudes ranging from 0 to 20,000 feet. This study looked at four distinct forms of fuel: humidified hydrogen, propane, methane, and JP-8 jet fuel. At each altitude and fuel type, maximum system efficiency was attained at loads of 40 L 60 percent design load, according to the research. At a portion load of 60% and an altitude of 20,000 feet, the system using methane fuel, internally steam reconstituted within the fuel cell, revealed to have the maximum system efficiency of 46.8% (LHV).

Keywords : Turbine engine, steam, fuel, propane

INTRODUCTION

The requirement for a high efficiency, long endurance propulsion system capable of handling huge on board electrical loads grows as unmanned aerial vehicles (UAVs) become more sophisticated and continue to push the limit. The combination of a gas turbine (GT) with a solid oxide fuel cell (SOFC) has previously shown to be a cost-effective and practical stationary power production system. Traditional solid oxide fuel cell hybrid gas turbine (SOFC/GT) power systems include massive heat exchangers, motor-driven blowers, and distinct combustion areas, which are not appropriate for an airborne platform. By merging the SOFC and combustor areas, as well as strategic plumbing that allows for chemical recovery, a SOFC combustor hybrid GT system avoids the need for such massive equipment. These hybrid systems can have lower power degradation characteristics at high altitudes than typical heat-based power systems because to the incorporation of a fuel cell module into a GT engine. At higher elevations, traditional heat-based power systems suffer significant performance deterioration. This power loss is exacerbated by the compressor's reduced available air

supply. At 20,000 feet, the Capstone C30 micro turbine, for example, decreases to 45 percent of its maximum power, a 55 percent reduction in output (Capstone 2006). The vast bulk of published research focuses on fixed SOFC/GT system performance and simulation, with only a handful addressing applications for aerial platforms. Despite this, fixed and mobile SOFC/GTs have the same unique component, the SOFC. Because the physics and chemistry of the SOFC are the same in both applications, researching stationary systems may teach us a lot about how they work and how we might apply it to aerial platforms. A number of articles relevant to this field of study were examined and used as resources. A SOFC/GT power system numerical model for an auxiliary power unit was developed by Chinda and Brault (2012) of the College of Industrial Technology at King Mongkut's University of Technology, North Bangkok. For a long-range, 300-passenger aeroplane, their auxiliary power unit was intended to produce 440 kW of net electrical power. In comparison to a similar model with a cycle efficiency of 42.0 percent, their SOFC/GT hybrid model achieved system efficiencies of 45.1 percent. An study was conducted to

establish the ideal design of the SOFC, compressor, combustor, heat exchanger, and GT, resulting in a high-efficiency system. The setup utilised by Chinda and Brault was as follows: air is compressed by a compressor, the air is then heated via a heat exchanger by exhaust gases from the gas turbine, and both air (oxidant) and hydrogen (fuel) are then given to the SOFC. The SOFC generates both power and high-pressure, high-temperature exhaust. In a combustor, the unspent SOFC fuel and high temperature and pressure SOFC cathode effluent are combusted. This heat is then utilised to warm the fuel that goes into the SOFC before being supplied to the turbine to expand and generate even more electricity. In terms of temperature balance throughout the cell stack, this setup permits the SOFC to be self-sustaining. The cycle efficiency is improved by using waste heat from the SOFC in the gas turbine. Extreme temperatures can be attained at particular flow rates and heat transfer coefficients, affecting the compressor and gas turbine's performance. The authors were able to tune their fuel and oxidant flow rates using this research to reach a 45.1 percent cycle efficiency.

SOFC and fuel processing models were created by Freeh, Pratt, and Brouwer (2004) and included in the Numerical Propulsion Systems Simulation (NPSS) software package. The NPSS is a computational architecture developed by the National Aeronautics and Space Administration (NASA) to help in numerical propulsion system simulation. To test

integrated model capabilities, a generic SOFC/GT system was modelled in the NPSS software package, with no parameters adjusted. An SOFC, compressor, turbine, steam reformer, and various heat exchangers were all part of the modelled system. The main fuel source for the simulation was a kerosene-type jet fuel Jet-A, which was portrayed as.

Solid Oxide Fuel Cells

Planar and tubular SOFCs are the two most frequent geometries. The electrodes and electrolyte are stacked flat sandwich style in the planar shape. This layout necessitates the construction of extra flow structures for the fuel and oxidant streams in order to maintain fuel and oxidant separation. In comparison to a planar SOFC, the tubular shape provides enhanced mechanical stability due to the stiff cylindrical form. The tubular SOFC is a superior choice for use in aerial platforms because of its increased mechanical stability. Tubular SOFCs with a capped end improve the mechanical stability of the cell while also minimising the risk of leaks owing to the fewer connection points.

Anode or cathode support is used in fuel cells. An anode-supported SOFC was modelled for the current study. The anode material provides the primary support for an anode-supported fuel cell. The electrode – electrolyte stack is then formed by applying the electrolyte and cathode layers on top of the anode material. A design and electrode – electrolyte stack up for an anode supported SOFC are shown in Figure 1.

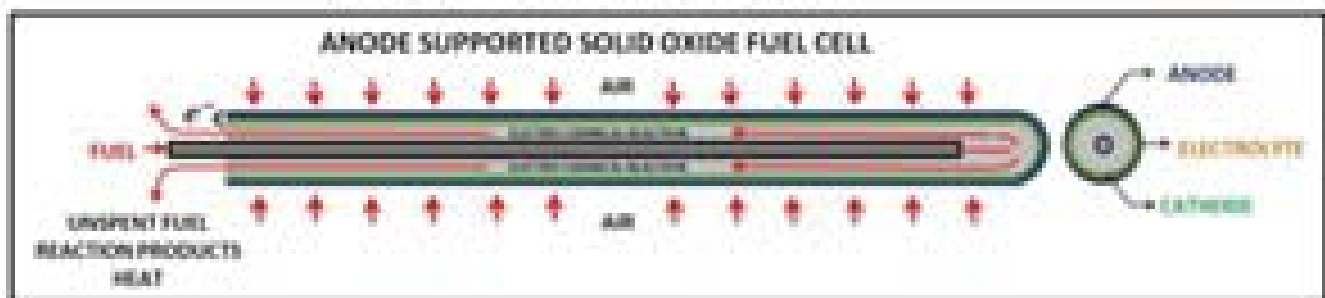


Figure 1: Anode Supported SOFC Schematic.

The current SOFC is based on an anode-supported fuel cell using Yttria-Stabilized Zirconia (YSZ) as the electrolyte, a Nickel – Yttria-Stabilized Zirconia (Ni-YSZ) anode, and a Lanthanum Strontium Manganite – Yttria-Stabilized Zirconia cathode (LSM-YSZ). Ni-YSZ and LSM-YSZ are both ceramic MIECs (mixed ionic-electronic conductors). These MIECs aid in increasing electrochemical reactivity at

both the electrode-electrolyte and electrode-electrolyte interfaces, resulting in improved performance. A vacancy hopping mechanism transports oxygen ions across the YSZ electrolyte. When Yttria is added to a Zirconia lattice, oxygen vacancies appear all throughout the lattice. The electrolyte's charge neutrality is maintained by these oxygen vacancies. (Caputo, Chao, and Huang 2007) and (Kilo, et al. 2003) have

done extensive research in this field and found that the YSZ electrolyte's ionic conductivity is highest when the dopant concentration is 8 to 10 mole percent. The electrolyte conductivity falls at 10 mole percent. A YSZ electrolyte with a concentration of 10% was used in this investigation. The SOFC must be run at a high temperature (600-1000°C) to achieve significant oxygen ion transport via the YSZ electrolyte. Because of the high working temperature, this form of fuel cell is suited for use after the combustion area in a gas turbine.

SOFC Combustor / GT Model

What sets this system apart from other reported SOFC/GT hybrids is the unique combination of the SOFC combustor and the GT engine. Figure 2 depicts a conventional gas turbine engine concept.

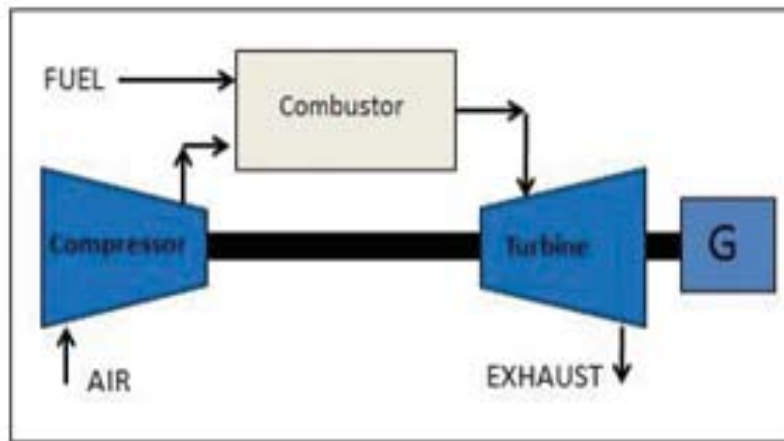


Figure 2: Traditional Gas Turbine Engine Schematic.

Fuel and a high-pressure oxidant are burned in a combustion chamber to create high-temperature exhaust gas in this system. This high-temperature exhaust gas is subsequently transferred to expand within the turbine, resulting in push or the turning of an electrical generator. The poor transfer of chemical energy within the fuel to useable energy is the flaw in this system. This usable energy is often in the form of electrical or mechanical (propulsive) work in UAV systems. During the conversion of chemical energy to thermal / heat energy, the typical method wastes energy.

Each energy conversion process degrades the energy's quality, beginning with high-quality chemical energy and ending with lower-quality thermal energy. The modelled SOFC combustor / GT makes advantage of the above-mentioned lost energy. A fuel cell stack may be added to the system to provide extra electrical energy at a reasonable cost while still maintaining a high-quality exhaust gas stream for the turbine engine. The fuel cell stack adds weight to the system, which is the only disadvantage. Figure 3 depicts the SOFC/GT system that was modelled.

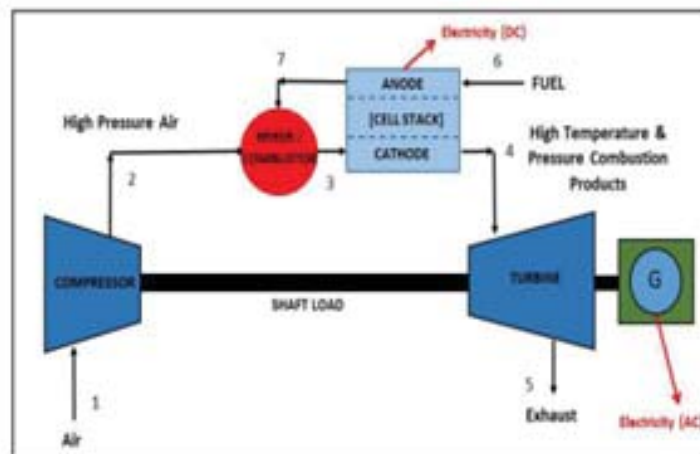


Figure 3: SOFC/GT Schematic.

The compressor and turbine function normally in this hybrid system, but air and fuel are also supplied to the SOFC, which produces extra energy capable of powering onboard electronics or supporting other electrical loads required during flight. The piping of the SOFC combustor to the GT engine is a unique characteristic of this system. All essential components and piping between the GT and SOFC combustor are shown in Figure 3. To offer an in-depth look into operating features, the system has been divided down into seven separate states. The compression of atmospheric air is represented by states 1–2. At the anode inlet, the fuel is delivered at state 6. In the combustion chamber, compressed air and unspent fuel from states 2 and 7 combine and burn, resulting in non-oxygen depleted high temperature combustion products. The SOFC's cathode side receives the high-temperature combustion products. Due to heat creation within the cell, the temperature of the cathode stream rises as it passes along the cell. The high-temperature exhaust is then expanded between states 4 and 5 in the turbine. Between stages 6 and 7, power is generated by converting fuel energy to electrical energy directly through electrochemical processes, and between states 4 and 5, power is generated by the expansion of hot SOFC exhaust through the GT.

Steady-State Part Load Performance Analysis

The SOFC/GT model was built to operate at maximum power at sea level, and the SOFC stack was tailored to commercially

available gas turbine characteristics for this study. A mathematical controller was designed to maintain a 1093 K turbine inlet temperature and a 170°C fuel cell stack temperature gradient, which were both tuned to preserve chemical stability within the cell. The fuel usage of the SOFC cell was not permitted to fluctuate throughout scoping runs, causing the cell temperature gradient to rise exponentially at lower part loads. The fuel use needs to be flexible to maintain the 170°C gradient under all operating situations, it was found. The SOFC Combustor / Hybrid GT model was used to perform a steady-state part load performance investigation across an altitude range of 0 Y 20,000 feet and a part load range of 10 L 100 percent. This study looked at humidified hydrogen, methane, propane, and JP-8 jet fuel, which are all distinct forms of fuel. The humidified hydrogen model ran on a 97 percent hydrogen, 3 percent water vapour fuel mix. Methane fuel was modelled in two ways: catalytic partial oxidation (POX) of the methane gas and direct steam reformation of the methane within the cell (SR). A catalytic partial oxidation of propane gas was used to represent the propane scenario.

The hydrogen yield for each of the fuel 28 processing methods modeled is shown below in Table 1. A detailed chemical analysis of the fuel processing methods is discussed in Appendix C.

Fuel	Hydrogen Yield (Y_{H_2})
CH_4 – Steam Reformation	80 %
CH_4 – Partial Oxidation	75 %
JP-8 – Steam Reformation	75 %
JP-8 – Partial Oxidation	67.5 %
C_3H_8 – Partial Oxidation	70 %

Table 1: Fuel Processing - Hydrogen Yield.

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Steady-State Part Load Performance Analysis

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Fuel	Number of Cells	SOFC Power (kW)	GT Power (KW)	Total Power (kW)
CH_4 – Steam Reformation	215	22.85	5.12	27.97
JP-8 – Steam Reformation	200	21.49	5.21	26.7
H_2 - Humidified	180	21.34	4.63	25.97
CH_4 – Partial Oxidation	180	19.76	5.08	24.84
JP-8 – Partial Oxidation	180	19.39	5.45	24.84
C_3H_8 – Partial Oxidation	180	19.49	5.25	24.74

Table 2: Maximum System Sizes – Sea-Level at Full Load

RESULTS AND DISCUSSION

The SOFC/GT system based on steam reformation of methane has a system efficiency of 3% higher than the steam reformed JP-8, 30.4 percent higher than the humidified hydrogen system, 40.9 percent higher than the partial oxidation of methane system, 56 percent higher than the partial oxidation of JP-8 system, and 51.9 percent higher than the partial oxidation of propane system. Figures 4 through 6 show the efficiency of the system vs portion load for each fuel type.

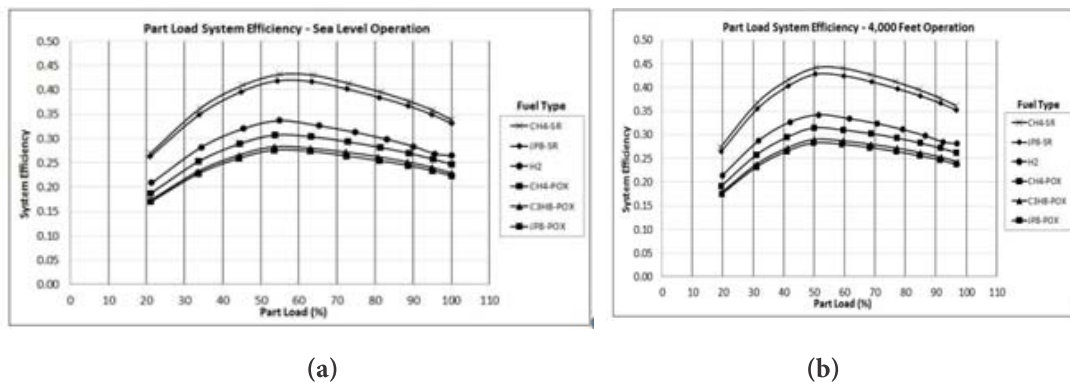


Figure 4: System Efficiency versus Part Load: (a) Sea-Level; (b) 4,000 ft.

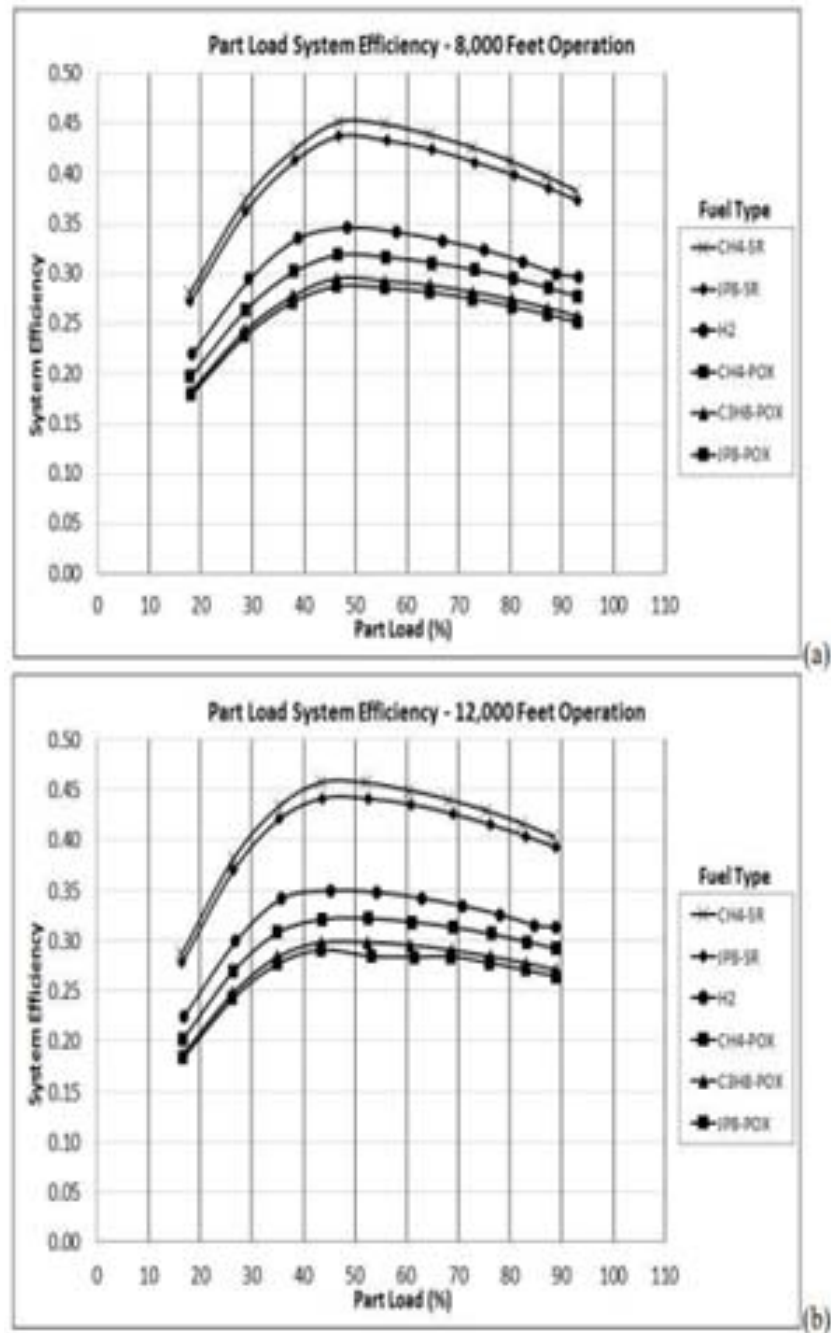


Figure 5: System Efficiency versus Part Load: (a) 8,000 ft; (b) 12,000 ft.

Figures 4 through 6 demonstrate how large of an influence spontaneous internal reformation of methane fuel has on system efficiency. Because of the high operating temperature of the SOFC, no unique internal catalyst would be required to execute the fuel reformation, unlike in an air POX reactor. The highest efficiency occurs around 40 to 50 percent load in each situation. Below 40% load, system efficiency plummets, and beyond 50% load, system efficiency plummets. The efficiency of the SOFC/GT system drops dramatically below 40 percent load. Because the turbine speed saturates at 55,000 revolutions per minute below 40 percent load, this is the case

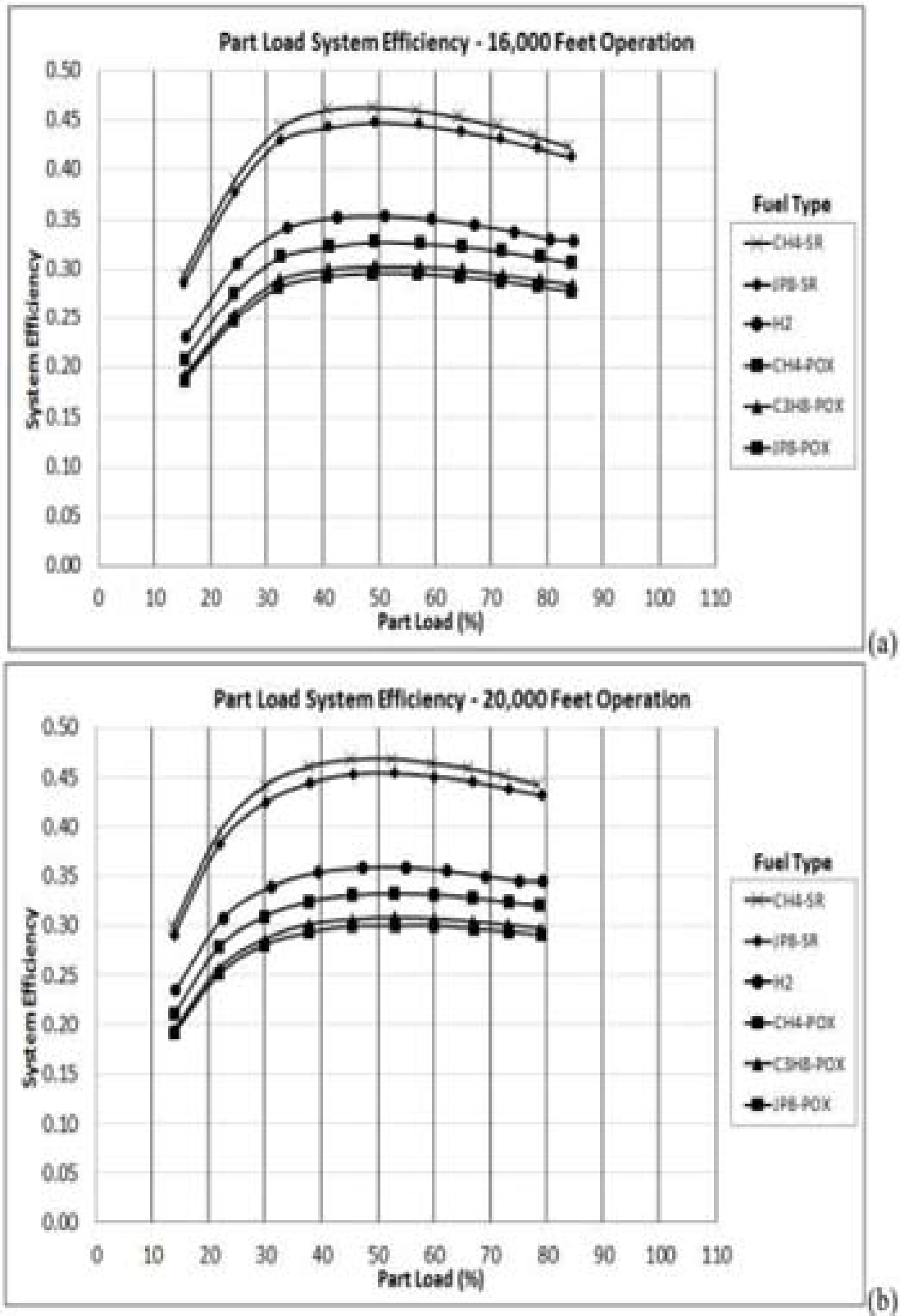


Figure 6: System Efficiency versus Part Load: (a) 16,000 ft; (b) 20,000 ft.

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