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FUEL PARAMETER AND QUALITY CONSTRAINTS FOR MICROTURBINE DISTRIBUTED GENERATORS

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ABSTRACT

Distributed generation (DG) technologies are currently being discussed as the new paradigm for the electricity infrastructure, owing to growth in electric loads, de-regulated markets, and reliability constraints, emission control limitations , and the huge capital investments with minimal rates of return associated with central station generation. Some DG technologies are critically dependent on the fuel quality and supply parameters for optimal power delivery and overall economic operation. Currently, most DG technologies are expensive to install, operate and maintain. One of the factors that could enable feasible and economic viability for installation of microturbines is the supply of fuel with the characteristics appropriate to DG designs [1]. This paper deals with the performance indices of Microturbine DG units and analyzes their dependency on fuel characteristics for economical and optimal performance.

KEYWORDS

Microturbines, microturbine performance, microturbine economics, fuel characteristics.

NOMENCLATURE

AUL	Average Useful life (Hours)
P_{ONET}	Net Power Output (kW)
P_T	Turbine Power output (kW)
P_C	Power Input to the Compressor (kW)
P_{FC}	Power Input to the Fuel Compressor (kW)
P_{fric}	Total System Friction Losses (kW)
$P_{Bearing}$	Total System Bearing Losses (kW)
P_{Con}	Electrical Conversion Losses (kW)
η_{is}	Efficiency of Isentropic Compression
η_{tot}	Total efficiency (LHV)
P_{Exht}	Exhaust Thermal Power (kW)
$P_{F(I)}$	Fuel Power Input (Btu/hr or equivalent kW)
m_{CP}	Mass flow of Combustion Products (kg/sec)
m_A	Mass flow of Air (kg/sec)
m_F	Mass flow of fuel (kg/sec)
EHR	Electric Heat Rate (Btu/kWhr)
SFC	Specific Fuel Consumption ($/kWhr)
HRR	Heat Release Rate (kJ/m^3)
FFR	Fuel Flow Rate (kJ/hr or Btu/hr)
FHC	Fuel Heat content (Btu/ ft^3 or MJ/m^3)
IFP	Inlet Fuel Pressure (psig)
K_S	Distribution System Fuel Pressure (psig)
Z_{FC}	Pressure Ratio of the Fuel Compressor
DP	Pressure loss in the Fuel Compressor (psig)
X_V	Volume rate of fuel flow (m^3/hr)
FQI	Fuel Quality Index
F	Faraday Constant (Coulombs)
C_p	Specific Heat at Constant Pressure (J/kg K)
T	Temperature (K)
Υ	Ratio of Specific Heats
R	Universal Gas constant (J/kg K)
Δg_F	Change in Molar Gibbs free energy (kJ/mole)
Δh_F	Molar enthalpy of formation (kJ/mole)
μ_F	Fuel Utilization Coefficient
P_e	Electrical Power rating (VA)
I	Current (Amperes)
Krpm	Kilo Revolutions per Minute
Psig	Pound per square Inch gauge
Psia	Pound per square Inch absolute
DC/AC	Direct /Alternating Current
LPNG	Low Pressure Natural Gas
CNG	Compressed Natural Gas
L/HHV	Low /High Heating Value
SCFM	Standard Cubic Feet per Minute
STP	Standard Temperature Pressure
MTG	Microturbine Generator

INTRODUCTION

In a microturbine generator, a rotating electric machine is driven by a small gas turbine, called a microturbine. The turbine operates on the Brayton (constant pressure) cycle. Microturbine generators are high-speed machines, commonly single-shaft in design and typically consisting of a single-stage, radial flow compressor, a combustor, a power turbine (expander) and a recuperator. The turbo-compressor assembly runs at about 100 krpm. Air at atmospheric pressure and temperature is compressed to about 50 to 75 Psig in the compressor. The compressed air at around 350^{o}F is preheated in the recuperator (carrying hot turbine exhaust gas at around 1200^{o}F) and burned with a controlled amount of high-pressure fuel in the combustor. The combustion products at high temperature (about 1700^{o}F) and high pressure are expanded over the turbine blades to produce shaft horsepower. In systems with Combined Heating and Power (CHP) operation the exhaust gases are discharged into the atmosphere through a domestic heating/cooling system after extracting most of the heat in the recuperator. The electrical generator is generally a high-speed permanent magnet alternator. The high frequency AC power generated is converted to DC using efficient rectifier circuits and the DC power obtained is converted back to 60Hz AC using advanced inverter circuits. Generally the AC output is of the range of 350-480 V, 60 Hz, 3-Phase, 3-or 4-wire wye .[2,3]

MERITS AND DEMERITS OF MICROTURBINE GENERATORS

- Compact design and size, enabling better portability and installation in residential areas.
- Durable, low maintenance, and proven technology.
- Simple design with good potential for large-scale manufacturing and installation.
- Highly adapted to domestic power generation due to sizeable cost savings with CHP operation.
- Good load following capabilities enabling stand-alone and grid-connected modes of operation with minimal electronics.
- Ability to operate on a variety of fuels (LPNG, CNG, gaseous propane, diesel, kerosene and landfill gas) with minimum or no retrofits.
- Very useful, and could prove highly economical, for peak-shaving applications.
- Low fuel efficiency; efficiency is dependent on the inlet fuel parameters.
- Noisy operation needs additional equipment and soundproofing for control of noise levels.

Operating life at design efficiency is relatively short and requires inspection, overhaul and routine maintenance.

DEFINITION OF THE CONSTRAINT

Microturbines are one of the most promising DG technologies. As they stand now, this technology is too expensive for extensive installation in most domestic and commercial applications. One of the primary constraints that exists, in addition to the high costs of material, complicated design, and complex manufacturing requirements, is the efficiency, cost, size and maintenance of auxiliary equipment to maintain the desired physical properties of fuels. These overhead costs are in addition to overhead incurred due to possible chemical and particle contamination of fuel. Performance indices and emission limits are dependent on fuel properties and fuel composition, though efforts are on to build microturbines that are less sensitive to fuel parameter deviations. If achieved, these will increase design costs. However, most of these problems could be eliminated if the fuel supply and distribution systems deliver the right kind and the right quality of fuel. With constraints and a wide range of safety norms already in place for the fuel distribution infrastructure, these demands may not be feasible. This paper deals with the analysis of some of the critical performance indices that are directly or indirectly dependent on fuel characteristics for microturbines. The analysis helps to understand how the economics of power generation for distributed generators varies with varying performance levels, owing to varying fuel characteristics and varying fuel chemistry.

PERFORMANCE INDICES AND FUEL PARAMETERS

The main performance indices of a microturbine generator system (without CHP) are:

Net Power Output (P_{ONET})

The net power output is the electric Power output in kW that is available to supply the electric load. P_{ONET} is equal to the gross mechanical power minus the summation of parasitic power, friction and bearing losses, and conversion losses. The parasitic power is mainly the power expended to drive the air and fuel compressors. Mechanical, friction and bearing losses are negligibly small. Conversion losses are the electric power losses that occur in rectifier and inverter circuits for AC-DC conversion.

$$P_{ONET} = P_T - \sum(P_C + P_{FC} + P_{fric} + P_{Bearing} + P_{Con}) \qquad (1)$$

Total efficiency (η_{tot}) LHV

The total efficiency of the microturbine generator system is the ratio of the summation of the net power output and the net heat released at the exhaust to the total system fuel input (LHV).

$$\eta_{tot} = \sum(P_{O(NET)t} + P_{Exht})/(293 * P_{F(I)}) \qquad (2)$$

Specific Power Output (P_O)

The specific power output is referred to as the summation of the power generated per unit mass flow (kg per second).

$$P_O = \sum (\underline{P_T}/m_{CP}) + (\underline{P_C}/m_A) + (\underline{P_{FC}}/m_F) \qquad (3)$$

Electric Heat Rate (EHR) LHV

Electric heat rate is the total amount of fuel burned per unit of electrical energy generated.

$$EHR = P_{F(I)}/P_{ONET} \qquad (4)$$

Specific Fuel Cost (SFC)

Specific fuel cost is the total cost of fuel per unit of electrical energy delivered to the load.

$$SFC = (P_{F(I)}) * (\text{Fuel cost in \$ per MBtu}/P_{O(NET)}) \qquad (5)$$

Emissions

Emissions for microturbine generators are expressed in ppmV (parts per million by volume) or lb/MWhr. The emissions from microturbines are mainly oxides of nitrogen (NO_X) with very small traces of carbon monoxide (CO), sulfur dioxide (SO_2) and carbon dioxide (CO_2).

Average Useful Life (AUL)

The average useful life of the turbine is the period over which it generates power equal to or less than its rated value at the design efficiency..

Heat Release Rate (HRR)

The amount of heat released by the combustion of fuel in the combustion chamber (combustor) is a vital factor for the efficiency and the net power output for the microturbine

HRR = (FFR*FHC)/(Primary Volume* Pressure ratio) (6)

FHC in the above equation is the lower heating value of fuel. Pressure-ratio is the ratio of the pressure of the combustion products to that of the fuel-to-air mixture [4]. In the actual Brayton cycle, (or the non-ideal Brayton Cycle) pressure drops due to heat addition in the combustor. Thus pressure-ratio is always lower than one, contributing to higher HRR values per unit fuel consumption.

The performances indices mentioned above are dependent on fuel parameters, fuel quality, ambient conditions and electrical/thermal loads. Fuel parameters are:

Inlet Fuel Pressure (IFP)

IFP is the pressure of the fuel at the point of injection into the combustor. IFP is dependent on the supply line pressure, measured in the local fuel distribution lines. Typical values of supply line fuel pressure are 0.5-1.5 psig. Most microturbine systems require a fuel compressor to obtain an IFP that is slightly greater than the pressure of air at the compressor outlet. Hence IFP is a function of the pressure of pressure in the fuel distribution system (K_S) and the pressure ratio of the fuel compressor (Z_{FC}) or the gain function for a pressure controller.

$IFP = (Z_{FC} * K_S) - DP$ (7)

DP is the pressure loss in the fuel compressor, or the difference in set point pressure and the actual regulated pressure.

$Z_{FC} \geq K_S$ at all times at ISO conditions (59^OF @ sea level)

Fuel Flow Rate (FFR) HHV value

The FRR is the higher heating value per hour of fuel flow from the fuel distribution system. FRR is expressed in terms of kJ/hr or in terms of Btu/hr.

FRR is a function of fuel heat content (FHC), volume rate of fuel flow (X_V, m^3/hr or SCFM) and the fuel quality index (FQI).

$FRR = FHC\ [HHV] *X_V$ (8)

at ISO conditions (59^OF @ sea level).

Fuel Quality Index (FQI)

Owing to low emission characteristics and easy availability, most commercial microturbine systems operate on natural gas (NG). The analysis presented in this paper is based on natural gas fired microturbine generators. The fuel quality index is a function of chemical composition of the fuel and fuel heat content (HHV).

Chemical composition

The chemical composition by volume of natural gas is never constant. For reasons of simplicity, the average chemical composition of natural gas by volume, is used in this paper:

Methane (CH_4): 95.52%; Ethane (C_2H_6): 2.627 %
Propane (C_3H_8):0.441 %; Butane (C_4H_{10}):0.136 %
Carbon Dioxide (CO_2):0.40%; Nitrogen (N_2): 0.74 %

Specific Gravity (rel. air =1): 0.580 [5,6]

Fuel Heat Content (FHC) or Heating Value HHV

The higher (gross) heating value of fuel is the quantity of heat produced by the combustion of a unit volume of gas in air under constant pressure, after cooling the combustion products to the initial temperature of air and gas (typically 77^oF) and after condensing the water vapor to liquid state. In other words HHV includes the latent heat of condensation of water vapor to water.

HHV or gross heating value ranges between 1000-1050 Btu/ ft^3 and 37.50-39.25 MJ/m^3. The lower (net) heating value of fuel (LHV) is equal to the gross heating value (HHV) minus the latent heat of vaporization of the water vapor formed by the combustion of hydrogen in the fuel. For all calculations in this paper unless otherwise mentioned, HHV= 1.11 * LHV.

Ambient Conditions:

Ambient Temperature: The performance of microturbines depends on ambient temperature. At increased air temperatures, the workload on the compressor increases due to reduced airflow mass rate (due to decline in density of air), resulting in lower net power output (P_{ONET}) and a lower total efficiency (η_{tot}).

Altitude: The efficiency (η_{tot}) also reduces with increased altitude. At higher altitudes, atmospheric pressure reduces and the compressor needs more power to compress the air to the rated value. Thus, at higher altitudes, the performance of microturbine generators drops below rated values.

Electrical Load:

Microturbine generators are designed to operate at full rated efficiency only under full load conditions. The fractional load performance of microturbines is lower than full load performance because the mechanical power output is reduced proportionally with the decrease in electric load demand. The decrease in mechanical power is due to the combined effect of reduced mass flow and lower turbine air inlet temperatures.

DEPENDENCY ANALYSIS

To understand the dependency of the performance indices on fuel parameters and fuel quality the following basic analysis of an ideal open Brayton thermodynamic cycle is presented. Most modern commercial microturbines operate on the non-ideal open Brayton cycle with recuperation.

The functional block diagram of an open cycle Microturbine system is shown in Figure 1.

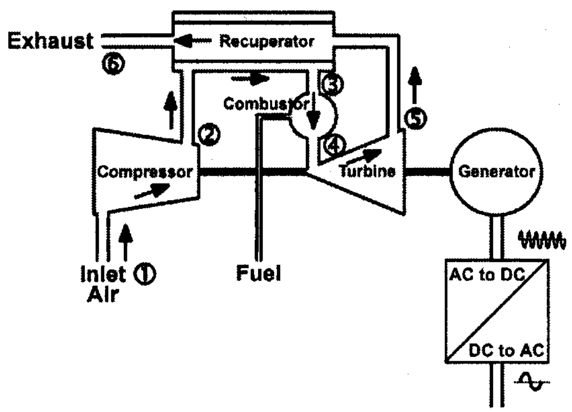
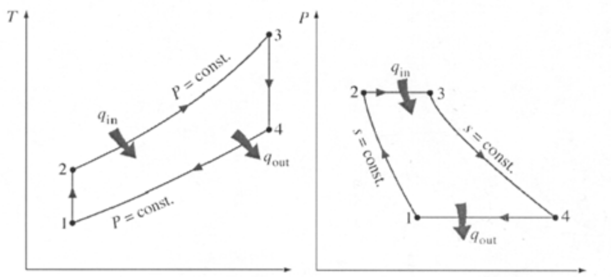


Fig. 1: Open cycle microturbine system [7]

Air at ambient temperature (59°F) and atmospheric temperature (14.73 psia) is drawn into a single-stage radial-flow compressor. The compressor compresses the air to about 80 psig depending on the design and the pressure-ratio (generally 3.5-4) of the compressor. The compressed air (80 psig, 400-430^{0}F) is admitted into the combustor. A fuel compressor (booster compressor) draws natural gas from the distribution supply line at a low pressure, $K_S = 0.5 – 2.0$ Psig, and compresses the gas to about 80 psig. The compressed fuel and the hot pressurized air are mixed in the combustor and burned at a low fuel-air ratio to ensure low NO_X emissions. The by-products of combustion (combustion gases) at high temperature (1300-1500^{0}F) and high pressure are expanded in the turbine (expander), resulting into a net torque at the turbine shaft. The turbine is designed with a pressure ratio in 3.5-4 to limit material stress, though a higher pressure ration yields higher specific power (P_O) and better efficiency. The exhaust gases from the turbine at low pressure (close to atmospheric pressure) but high temperature (1200^{0}F) could be used for CHP applications. If a recuperator is used, it reduces the effective fuel-input and enhances the heat-rate in addition to improving the total efficiency (η_{tot}) [10]. The T-*s* and P-*v* diagrams are shown in Fig. 2.



(a) *T*-*s* diagram (b) *P*- υdiagram

Fig. 2: Diagrams for Ideal Open Brayton cycle [9]

From basic thermodynamics the specific work (work per unit mass flow rate) for a compressor is

$$-W_C = \int_1^2 C_p(T)\, dT$$

Subscripts 1 and 2 denote the corresponding states as shown on the T-*S* and P-*V* diagrams. The negative sign for work represents that work is done on the fluid. C_P is assumed to be the average of the values at inlet and outlet. Integrating between state points 1 and 2 we get,

$$-W_C = C_p T_1 [T_2/T_1 - 1]$$

Assuming reversible isentropic compression (adiabatic process - no heat add to or extracted out of the system)

$$T_{2,is}/T_1 = (P_2/P_1)^{[\Upsilon/\Upsilon - 1]}$$

and

$$-W_C = [\Upsilon/(\Upsilon - 1)]RT_1[(P2/P_1)^{[\Upsilon/\Upsilon - 1]} - 1] * (1/\eta_{is}) \tag{9}$$

Υ is the ratio of C_P to C_V and R is the universal gas constant.

The efficiency of isentropic compression is defined as

$$\eta_{is} = (T_{2,is} - T_1) / (T_2 - T_1)$$

If m_A is the total mass flow rate through the compressor then the actual power needed to drive the compressor is

$$P_C = m_A . W_C \tag{10}$$

For the turbine the equations for specific work and power are

$$W_T = \eta_{is} [\Upsilon/\Upsilon - 1] R T_3 \{1 - (P_4/P_3)^{[\Upsilon/\Upsilon - 1]}\} \tag{11}$$

$$\text{And } P_T = m_{CP} W_T \tag{12}$$

m_{CP} is the mass flow of the gaseous combustion products in the turbine. Subscripts 3 and 4 represent the thermodynamic states before and after the expansion in the turbine [10].

Dependency 1: Inlet fuel pressure (IFP)

Higher IFP is mandatory and critical for better performance of MTGs as demonstrated in the following dependencies:

Higher IFP enhances the specific work W_T for the turbine (equation 11) and hence yields higher turbine power output P_T (equation 12) per unit fuel energy.

Net power output $P_{ONET,}$ which is the electrical power output, increases, but at the expense of parasitic power consumption for the air and fuel compressors (eq. 1).

The Electric heat rate (fuel input per unit electricity generated) improves because of higher P_{ONET} with the same quantity of fuel injected into the combustor (equation 4)

Specific fuel cost (equation 5) decreases due to reduced fuel consumption per unit electric energy.

HRR improves because the pressure-ratio for the combustor decreases with higher values of IFP (eq. 6).

Total efficiency (equation 2) for the MTG system increases.

Higher pressure of fuel at the combustor inlet enables lower fuel flows. The lower fuel flow enables combustor operation with a lean air/fuel mixture, which avoids lower flame local hot spots, as the peak flame temperature is less than the stoichiometric adiabatic flame temperature. The elimination of hot spots in the lower flame region suppresses thermal NO_X formation.

The above-mentioned dependencies improve the performance of the MTG and also effect cost savings owing to better utilization of fuel. However, higher IFP values cause more power to be spent to drive the air and fuel compressors. This is clear from equations (9), (10) and (1). Typically the air compressor utilizes as much as two-thirds and the fuel compressor uses one-seventeenth of the power generated by the turbine at full-load [7].

In addition to the need for more parasitic power, higher values of IFP impose the need for better materials capable of sustaining thermal stresses at high pressure flows, and critical designs for the compressor and the turbine.

The design of the compressor and the turbine are crucial for the AUL of the microturbine generator system. The power consumption by the fuel compressor can be reduced if the fuel supplied by the gas distribution system is at higher pressure than the current pressure values measured in most commercial and residential areas. The implicit conclusion from equation (7) is that the fuel compressor design could be simplified if the value of K_S tends to approach the value of IFP. A simpler design implies lower Z_{FC} without or with a negligible value error correction function represented by DP.

Dependency 2: Fuel Flow Rate (FFR) and Fuel Heat Content (FHC)

The FFR represents the average quantity of heat added into the system. FFR (Btu/hr) depends on the heat content of the fuel (equation 8). A higher value of FFR adds a higher amount of heat for the same volume of fuel flowing into the combustor. The dependencies are:

Higher FFR yields higher temperature per unit fuel consumption at the turbine inlet (T_3), which improves the specific work output and the turbine output (eqs. 11, 12).

Enhanced turbine power output increase the net gross power output and the total efficiency of the system (equations 1, 2)

Specific power output and the electric heat rate vary in proportion to variation in FFR. Higher values of FFR improve specific power output and the electric heat rate of the MTG system (equations 3, 4).

Higher values of FFR improve the efficiency of the combustor because of higher HRR (equation 6).

Specific fuel cost decreases with higher values of FFR because the fuel requirement per unit of heat energy released during combustion reduces for the same value of net power output delivered (equation 5).

Dependency 3: Chemical Composition of Fuel

The chemical composition of fuel (natural gas) affects the heating value of fuel and results in higher fuel consumption for low quality fuel.

The average chemical composition of natural gas fuel-air ratio, flame temperature and the combustor design are critical for low NO_X and low CO emissions by volume. NO_X emissions for well-designed MTGs are typically of the order of less than 8-9 ppmV at 15% O_2 because NO_X emissions for natural gas driven engines and turbines depend mainly on thermal NO_X formation rather than chemically bound nitrogen. Natural gas has very low chemically bound nitrogen. The amount of CO_2 emitted is a function of the carbon percentage in the fuel. The average carbon content of natural gas is 34 lbs/MMBtu.

Dependency 4: Ambient Temperature, Altitude and the Electrical Load

Figures 3, 4 and 5 show the microturbine performance for varying temperature, altitude and electrical load.[8,10]

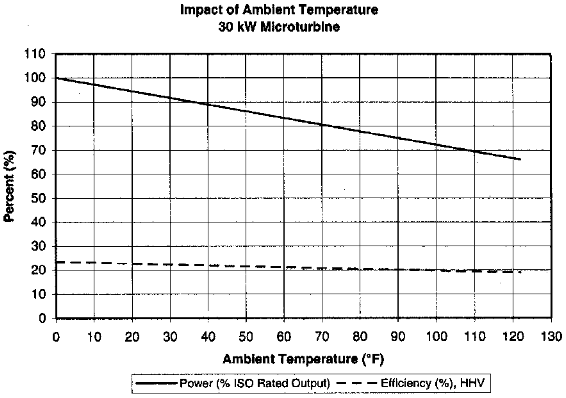


Fig. 3: Microturbine Performance and Ambient Temperature [10]

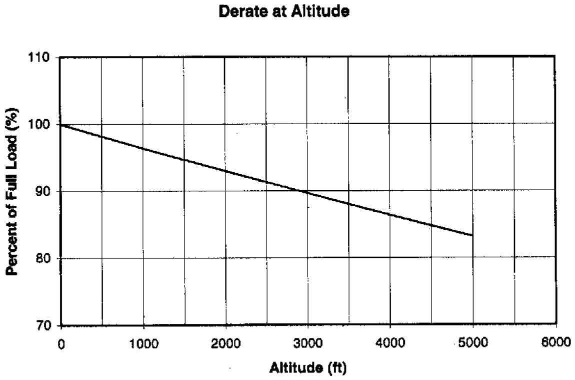


Fig. 4 : Microturbine Performance and Altitude [10]

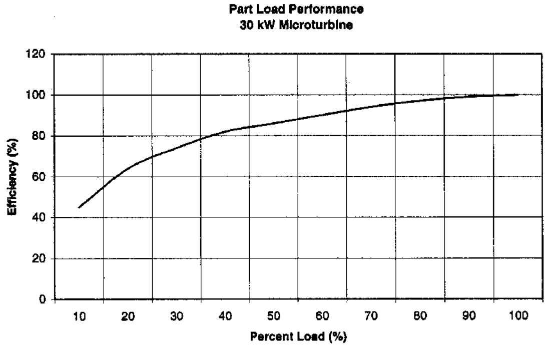


Fig. 5: Microturbine Performance with Electrical Load [10]

CONCLUSIONS

Fuel quality and supply parameters that affect the performance of a microturbine electric generator have been summarized in this paper. This is one of the issues that must be evaluated to determine the economic feasibility of microturbines [1]. Similar work is needed on the other issues.

The authors are collecting data from commercially available microturbine generators. These generators will then be analyzed for the effects of variations in fuel quality and supply.

Fuel quality and supply issues also affect any other distributed generation technology relying on natural gas. The most notable such technology is fuel cells. The authors are doing an analysis for fuel cells similar to that presented in this paper. Commercial fuel cells will then be analyzed.

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