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Modeling of internal combustion engine based cogeneration systems for residential applications

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Abstract

A parametric model that can be used in the design and techno-economic evaluation of internal combustion engine (ICE) based cogeneration systems for residential use is presented. The model, which is suitable to be incorporated into a building simulation program, includes sub-models for internal combustion engines and generators, electrical/thermal storage systems, and secondary system components (e.g. controllers), and is capable of simulating the performance of these systems in 15-min time steps. Water storage tanks for thermal storage and electrochemical (battery) systems for electrical storage are modeled. The parametric model provides users with useful information about the cogeneration system performance in response to a building's electrical and thermal demands. This paper presents the model, and the results of sensitivity analyses obtained using the model with a building simulation program. The results demonstrate the capabilities of the model and provide an insight into the energetic performance of ICE based cogeneration systems.

Keywords: Residential cogeneration; Residential CHP; Micro-generation; Micro-cogeneration; Micro-CHP

1. Introduction

There is a growing potential for the use of cogeneration systems[1] in the residential sector because they have the ability to produce both useful thermal energy and electricity from a single source of fuel such as oil or natural gas, with the potential to reduce overall energy expenditure due to their higher energy conversion efficiency compared to that of conventional energy conversion systems. In cogeneration systems, the efficiency of energy conversion increases to over 80% (based on lower heating value, LHV[2]) as compared to an average of 30–35% for conventional fossil fuel fired electricity generation systems and up to 55% in combined cycle power plants, such as combined cycle gas turbine. This increase in energy efficiency can result in lower energy expenditures and reduction in greenhouse gas emissions when compared to the conventional methods of generating heat and electricity separately. The potential to reduce overall energy expenditures is especially critical for consumers considering the growing energy costs as prices for oil and natural gas continue to increase, at times in an unpredictable and/or volatile fashion.

Technologies suitable for residential cogeneration systems include reciprocating internal combustion engine (ICE), micro-turbine, fuel cell, and reciprocating external combustion Stirling engine based cogeneration systems. A comprehensive review and comparison of these systems is presented in Onovwiona and Ugursal [1] and Knight and Ugursal [2]. These reviews indicate that presently reciprocating internal combustion engines (ICE) are the prime mover of choice for residential cogeneration applications because of their well-proven technology, robust nature,

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[1] Also known as combined heat and power (CHP) systems.

[2] Many manufacturers Europe and Japan base engine power ratings in terms of the LHV of the fuel, in North America, the higher heating value (HHV) is usually used.

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Nomenclature

BSFC	brake specific fuel consumption	$P_{A,r}$	adjusted rated power
CF_a	correction factor for altitude and temperature	P_r	rated power
CF_t	correction factor for temperature	P_e	electrical power output
DHW	domestic hot water	Q_{th}	useful thermal output
EFFO	overall efficiency	SOC	state of charge
FU	useful thermal output	t	time
HPR	heat to power ratio	x	part load ratio
HHV	higher heating value	η_o	overall efficiency
ICE	internal combustion engine	η_Q	corrected thermal efficiency for cold start
LHV	lower heating value	η_{Qmax}	thermal efficiency not affected by cold start

reliability, and reasonable cost. However, they do need regular maintenance and servicing to ensure availability.[3] In addition to these advantages, the development of small household ICE cogenerators with low CO_2 and NO_x emissions by several manufacturers have largely addressed emission concerns. For example Honda Motor Co.[4] has developed a 1 kW electrical and 3 kW thermal output cogeneration unit based on a natural gas fired internal combustion engine, specifically designed for single-family applications, and with a reported overall energy efficiency of 85% (based on LHV). Owing to the improvements in cogeneration technologies and potential for energy cost savings, the residential cogeneration market is beginning to develop in many parts of the world, including North America, Europe and Japan [1,2]. For example, in 2003, United States developed a micro-CHP roadmap, and is funding several micro-CHP programs, including those for the residential sector.[5]

The interaction between a building's electrical and thermal demands and a cogeneration unit represents a complex thermodynamic system because of factors such as the occupants' electrical and domestic hot water (DHW) usage patterns, the house's space heating demands, weather, the cogeneration plant performance characteristics and operational strategy, as well as the operation of other HVAC components. This complexity requires a building performance modeling and simulation tool that is capable of evaluating the thermal performance of the building and cogeneration plant as an integrated, dynamic system. Thus, this paper presents a comprehensive computer simulation model designed to be incorporated into a building energy simulation software, in this case the ESP-r [3], to be used in the design, techno-economic evaluation and optimization of ICE based cogeneration and associated thermal/electrical storage systems for residential use, as well as some illustrative results obtained using the model.[6] The model includes sub-models for ICE/generator unit, electrical (lead-acid battery) and thermal (hot water) storage systems, and secondary system components (e.g. controllers), and is capable of simulating the performance of these systems in a given time step. In this work, a time step of 15 min is used. Information regarding brake specific fuel consumption (BSFC), electrical efficiency, fuel flow rate and heating value, and engine exhaust temperatures of ICE based cogeneration units obtained from the literature, experimental and manufacturers' data was used to develop mathematical relationships that describe the effect of engine load on the engine electrical efficiency, thermal power, fuel consumption. and greenhouse gas emissions. Also, mathematical relations describing the cold start behavior of an engine and the effect of ambient temperature and altitude on engine performance were developed. A detailed presentation of the model and results demonstrating its capabilities are presented in Onovwiona [4].

2. ICE cogeneration system modeling

In this work, the ICE cogeneration system is assumed to address the space and domestic hot water heating and electrical loads of the residence; cooling loads are not considered. The conceptual design adopted for the residential ICE cogeneration system with electrical and thermal storage is presented in Fig. 1.

Two operating scenarios are assumed for the ICE cogeneration system. The *electrical priority controller* scenario involves operating the ICE to follow the electric demand of the building, while the *constant output controller* scenario involves operating the ICE at the minimum brake specific

[3] Reliability is determined by the amount of unscheduled outage as a result of equipment failure, while availability is the proportion of time the cogeneration plant is available for use when needed.

[4] http://world.honda.com/news/2001/p010830.html.

[5] Further information is available from the following websites:http://www.eere.energy.gov/de/pdfs/micro_chp_roadmap.pdf http://www.energetics.com/depeerreview05/agenda.html.

[6] ESP-r was selected due to its powerful energy flow modeling capabilities, as well as its capability to solve for the thermal and electrical flows and balances throughout an entire building. Its open source code allows for continual evolution and expansion of the original software kernel as developed and validated by the Energy Systems Research Unit at the University of Strathclyde [3]. ESP-r was selected by CANMET Energy Technology Centre (CETC) as the preferred simulation engine for future Canadian building simulation tools. Detailed information on ESP-r can be obtained from http://www.esru.strath.ac.uk/Programs/ESP-r.htm.