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Investigation on zero grid-electricity design strategies of solid oxide fuel cell trigeneration system for high-rise building in hot and humid climate

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HIGHLIGHTS

- Two zero grid-electricity design strategies of SOFC-trigeneration system for high-rise building were proposed.
- The full- and the partial-SOFC-trigeneration systems would have 51.4% and 23.9% carbon emission cut respectively.
- The two zero grid-electricity strategies had corresponding electricity savings of 7.1% and 2.8%.
- As a whole, the full-SOFC-trigeneration assures both environmental and energy merits.

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ABSTRACT

Trigeneration, which is able to provide cooling, heating and power, has been advocated to be a sustainable solution for building use in the urban area. With the high-temperature feature and maintenance convenience, solid oxide fuel cell (SOFC) becomes a promising prime mover of trigeneration. In this study, two zero grid-electricity design strategies of SOFC-trigeneration system for high-rise building were proposed and evaluated. The first zero design approach, named full-SOFC strategy, is to design the rated capacity of SOFC by matching the demand peak of electrical power without the need of grid connection. The second one, called partial-SOFC strategy, is to satisfy the peak electrical demand partly by the SOFC and partly by the grid, but still maintaining net zero grid-electricity in a year time. In view of the system complexity and the component interaction of SOFC-trigeneration, the environmental and energy performances of different cases were evaluated through year-round dynamic simulation. Compared to the conventional provisions of cooling, heating and power for building, the full- and the partial-SOFC-trigeneration systems could have 51.4% and 23.9% carbon emission cut per annum respectively. In terms of year-round electricity demand, the two zero grid-electricity strategies had corresponding savings of 7.1% and 2.8%. As a whole, the full-SOFC-trigeneration assures both environmental and energy merits for high-rise building in the hot and humid climate.

1. Introduction

The efficiencies of classical power plants usually do not exceed 40%. To improve the situation, distributed power supply systems through cogeneration or even trigeneration can be employed in which the overall system efficiency can be in the range of 60–80% [1], depending on the type of prime mover and the temperature level of the heating requirement. Through such approach, the carbon emission can be greatly reduced. In trigeneration, the conventional prime mover is related to the thermodynamic cycle, such as internal combustion engine (ICE), gas turbine or steam turbine. Coupled with the generator set, these cycles are commonly used in electricity generation. In recent years, new thermodynamic cycles have been evolved, like Stirling engine (external combustion engine), mircoturbine and organic Rankine cycle [2]. As emerging technology, fuel cells are also possible to be the prime mover of trigeneration, as waste heat can be captured and utilized. The common types of fuel cells include proton exchange membrane fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells (MCFC) and SOFC. Both MCFC and SOFC are classified as high temperature fuel cells, since their operating temperature is over 600 °C.

For trigeneration, the latest technologies, benefits and characteristics, technical performances, utilization and development, linkage with renewable resources have been reviewed and consolidated [1,2]. It is found that the SOFC-driven trigeneration is worth being committed in further studies [3,4]. Comparison of trigeneration system using the prime movers of ICE, gas turbine, Stirling

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Nomenclature

COP	coefficient of performance of chiller	ICE	internal combustion engine
$T_{hw,s}$	hot water supply temperature from fuel cell (°C)	MCFC	molten carbon fuel cell
WHUF	waste heat utilization factor of fuel cell	SAF	supply air fan
η_e	electricity generation efficiency of fuel cell	SAV	supply air coil valve
η_o	overall efficiency of SOFC for trigeneration	SOFC	solid oxide fuel cell
HP	heat pump		

engine and SOFC were carried out for building application [5,6], and particular attention was paid on the criteria of technology and environmental impact. The SOFC is one of the potential choices for the prime mover due to its high efficiency in the electricity generation. Moreover, the high temperature flue gas can be used to provide hot water to drive an absorption chiller for space cooling and hot water for drinking simultaneously. In long-term, SOFC are considered as a more promising technology in fuel cells [7], since they are based on solid electrolyte without expensive catalysts. As their operating temperature is high and internal reforming is possible, a number of fuel types can be applied for hydrogen generation.

In building applications, Weber et al. [8] proposed a decentralized energy system using SOFC with double-effect absorption heat pump for office building. Through numerical simulation, the carbon reduction of the system could be over 30% against the conventional system. Zink et al. [9] conducted simulation study of an internal reforming tubular SOFC coupled with a single-stage absorption heat pump (HP) to generate electricity and cooling/heating for building. The overall efficiency of the SOFC-HP system was 87% for electricity and heating cogeneration, while 95.7% for electricity and cooling cogeneration. Malico et al. [10] designed a demonstration project of SOFC-driven trigeneration based on the electrical load for the hospital application. The trigeneration contained tubular SOFC, absorption chiller and gas boiler, which was added in order to supplement the thermal load of the hospital. Velumani et al. [11] modelled a trigeneration system including SOFC, microturbine and single-effect absorption chiller for distributed generation. A simulation model of the trigeneration system was developed and its performance was evaluated.

These previous studies of SOFC-driven trigeneration were mainly based on steady-state system simulation at the design conditions. However in the building applications, dynamic simulation is necessary in order to fully appraise the system performances with respect to changing building loads and climatic conditions. It is also essential to evaluate the components hence the system characteristics in different operating conditions. On the other hand, although trigeneration is well known to have good overall efficiency, the thermal efficiency would be over-estimated since it is not constant at the rated value. In fact, the thermal efficiency heavily depends on the quality of heat able to be extracted from the flue gas in different loading conditions. It would be more effective to evaluate the system performance based on the solid information, such as the manufacturer's data. Another question is how to realize the trigeneration technology for low carbon building design, especially the provision of cooling for those buildings in the hot-humid climate. And the design approach would be determinable to the capacity sizing of SOFC in the trigeneration system. Therefore, this study is to explore the system performances of SOFC-trigeneration in connection to sustainable strategies through year-round dynamic simulation.

The rest of this paper is organized as follows: Section 2 describes the system design of SOFC-trigeneration, covering the various component equipment for building cooling, heating and power. Section 3 states the design information of the trigeneration system and the building zone in this study, particularly the SOFC component model. Section 4 brings out the methodology of analysis for the two proposed zero grid-electricity design approaches – the full-SOFC strategy and the part-SOFC strategy. Section 5 discusses the results of the year-round system performances, the monthly variation of different performances and the effect on SOFC staging. Section 6 is the conclusion and recommendation.

2. System design of SOFC-trigeneration

Fig. 1 shows the schematic design of the SOFC-trigeneration system serving a multi-storey office building. The fuel reacts electrochemically with the air in the SOFC to generate electricity for the building zone. The unreacted fuel is burnt in the combustor and the hot exhaust flue gas is used to pre-heat the fuel and the air before passing to a hot water generator in which hot water is delivered. This hot water is used to drive the absorption chiller first. A hot water recuperator is placed downstream of the absorption chiller to provide hot water supply for the building zone. In the office building under hot and humid climate, the hot water is mainly used for drinking purpose. An auxiliary heater is installed in the hot potable water stream to supplement the hot water recuperator in order that the temperature of the hot drinking water can be maintained.

For the office building in the hot and humid city, the cooling demand is very high. Hence, the waste heat from the SOFC may not be sufficient to provide the necessary cooling requirement. In view of this, auxiliary vapor-compression chillers are involved when the cooling demand is high. Through the chilled water pumps, chilled water is provided to the cooling coil of the air handling unit, then conditioned air is delivered to the building zone by the supply air fan (SAF). As a two-way supply air valve (SAV) is used in each air handling unit, the secondary chilled water flow rate can be varying depending on the operating conditions. A chilled water bypass valve is employed so that the primary chilled water flow rate can be maintained constant. Cooling water pumps are used to remove the heat from chillers to cooling tower for heat rejection purpose. Consequently, a centralized SOFC-trigeneration system is designed for electricity supply, air-conditioning supply and hot water supply for the entire building.

In the proposed SOFC-trigeneration system, the design capacities of SOFC and chillers would be determined in a way that they are enough to satisfy both the electrical and thermal demands at any instant throughout a year. As a result, energy storage is not involved in the system design. In real application, energy storage can also be omitted since the grid connection can provide emergency power supply when necessary.

3. Details of system and building design under study

3.1. Building information

In this study, the SOFC-trigeneration system was designed to serve a 28-storey office building in the subtropical Hong Kong