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Novel performance curves to determine optimal operation of CCHP systems

Sayyed Faridoddin Afzali, Vladimir Mahalec*

Department of Chemical Engineering, McMaster University, 1280 Main St. West, Hamilton, ON L8S 4L8, Canada

HIGHLIGHTS

- Novel performance curve (NPC) to optimize CCHP operation.
- NPC considers changes in energy prices, fuel consumption and CO_2 emissions factors.
- NPC methodology leads to the better CCHP operation than other strategies.
- Thermal, electric, hybrid load following strategies are subset of NPC strategy.
- Match performance strategy is a subset of NPC strategy.

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ABSTRACT

Economic and environmental impact of a combined cooling, heating and power (CCHP) system depends not only on its structure but also on the way it is operated. In this paper, a novel methodology which utilizes overall optimal partial loads of power generation unit (PGU) and novel performance curves (NPC) is proposed to optimize CCHP operation. The PGU overall optimum partial loads for demands below and above the CCHP operating curve are determined based on the optimization criteria and system characteristics. Proposed methodology is flexible and adaptable; it accounts for energy prices, carbon dioxide emissions, primary energy consumption factors and load variations with the weather conditions. Other strategies, such as following match performance, hybrid load, electric load, and thermal load strategies are shown to be the special cases of the NPC methodology. The performance of a CCHP system which operates based on the NPC methodology is compared to the CCHP performances when following match performance, hybrid load, electric load, and thermal load strategies. The comparison is carried out for two small hotel buildings in San Francisco and Miami and residential buildings in Dalian having different energy demand profiles. These locations have different energy prices, carbon dioxide emissions and primary energy consumption factors. The proposed methodology leads to the best operation when compared to other operating strategies based on operating cost, carbon dioxide emissions, primary energy consumption and a combination of them which is not always the case for other operating strategies. Proposed methodology provides a unifying framework which includes all previously operating strategies.

1. Introduction

Combined cooling, heating and power systems (CCHP) are widely utilized as effective energy production systems to provide electricity, cooling and heating. Applications of CCHP systems have been increasing in large and small-scale buildings to solve the energy-related problems, such as increasing energy cost, increasing energy demand and environmental issues [1].

The use of CCHP systems has been investigated for various kinds of buildings, such as office buildings [2], hotels [3], residential buildings [4] and other types of commercial buildings. Electrical, cooling and heating demands of a building vary during a day and also vary throughout a year. The energy output of a CCHP system typically cannot match either the electrical demand or the heating load or the cooling load. As a result, scheduling of the CCHP operation, selecting an appropriate system configuration and a proper size of power generation unit are vital in order to achieve a high energy efficiency, economic benefits and also reduce the greenhouse gas (GHG) emissions.

There have been many papers dealing with different configurations of a CCHP system. The common and simple CCHP system comprises a power generation unit (PGU), a heat recovery system, a heating coil or a heat exchanger, an absorption chiller and a boiler [5]. To improve the cooling efficiency, an electric chiller has been added to the CCHP system to provide additional cooling from the electricity [6]. In order to

* Corresponding author.
E-mail address: mahalec@mcmaster.ca (V. Mahalec).

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Nomenclature

Acronyms

ATC	annual total cost
CCHP	combined cooling, heating and power
CDE	CO_2 emission
CHP	combined heat and power
COP	coefficient of performance
FEL	following the electrical load
FTL	following the thermal load
FHL	following hybrid load
FLB	following the load of the building
FSS	following seasonal strategy
GSHP	ground source heat pump
LB	lower bound
MP	match performance
NPC	novel CCHP performance curve
kW	kilowatt
ORC	Organic Rankine cycle
PEC	primary energy consumption
PGU	power generation unit

Variables

C	cost [$/kW]
E	electric energy [kW]
F	fuel energy [kW]
f	partial load of PGU
G	PEC ratio
k	CCHP operating curve equation
Q	heating energy [kW]
R	price ratio
S	CDE ratio
Cr	criteria

Greek

η	efficiency
μ	emission conversion factor
δ	objective function
Δ	increasing the objective function
φ	objective function
ω	weighting factor
ψ	performance curve

Subscripts

ab	heating to absorption chiller
ac	absorption chiller
b	base
boiler	boiler
cd	cooling demand
CDE	carbon dioxide emission
combination	a combination of criteria
cost	cost
d	demand
f	partial load
th	thermal
SP	separate production
UB	upper bound
diff	difference of LB and UB
E	electricity
ec	electric chiller
f	fuel
fb	partial load at base
fl	partial load at f
g	natural gas
grid	grid
hc	heating coil
hd	heating demand
i	number of criteria
LB	lower bound
min	minimum
max	maximum
nom	nominal
rec	recovery
SP	separate production
UB	upper bound

Superscripts

above	above the operating curve
below	below the operating curve
LHS	left-hand side
mid	mid-peak period
off	off-peak period
on	on-peak period
RHS	right-hand side

obtain a wide range of electric output to thermal output ratio, application of the thermal energy storage has been analyzed extensively [7]. Thermal energy storage can help manage CCHP thermal output to meet cooling and heating demands at peak loads. Mago et al. [8] investigated the operation of a combined heat and power system with dual power generation units and thermal energy storage. Song et al. [9] studied the performance of CCHP system utilized in a data center; the cooling storage was employed to store the excess cooling energy and then provide cooling energy when it was needed. Furthermore, a battery has been employed to manage the electric output of the system [10]. Fang et al. [11] investigated performance of a CCHP integrated with an organic ranking cycle (ORC) and an electric chiller by proposing a strategy which is applicable for a wide range of loads. Knizley et al. [12] compared performance of an ORC-CHP system to the conventional system in terms of operating cost, primary energy consumption (PEC) and carbon dioxide emissions (CDE). To attain flexibility in heating and cooling outputs, ground source heat pump (GSHP) was added to a CCHP system and analyzed in [13]. Liu et al. [14] analyzed performance of a CCHP system which included a GSHP and thermal energy storage. The CCHP performance was studied by assuming two types of PGU; gas turbine and an internal combustion engine. A CCHP system driven by gas–steam combined cycle was suggested for application in an educational center in China [15]. Distributed energy resources, such as solar energy and wind energy have been integrated with a CCHP system to enhance the efficiency of the system and reduce the pollution [16]. Fu et al. [17] studied the performance of a CCHP system consisting of an internal combustion engine, a flue gas heat exchanger, a jacket water heat exchanger and an absorption heat pump. They compared the operation of this system to the performance of conventional CHP system [18].

Operating strategies for CCHP systems have been studied in many papers. In the review below, we will summarize the extent of reduction as% of the specific objective; positive% means that the objective was reduced, negative% means that the objective was increased as a result of applying specific strategy. Following the electrical load (FEL) and following the thermal load (FTL) are two frequently used operating