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Evaluation of the energy performance of variable refrigerant flow systems using dynamic energy benchmarks based on data mining techniques

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HIGHLIGHTS

- We proposed a method to evaluate the dynamic energy performance of VRF systems.
- Dynamic energy benchmarks were established based on data mining techniques.
- Nine power consumption patterns were classified using DT analysis.
- Energy consumption rating system was developed to provide quantitative energy evaluation.
- Case study was conducted under various refrigerant charge faults of the VRF system.

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ABSTRACT

The variable refrigerant flow (VRF) system has extremely different energy performance at various operation conditions. Its power consumption is inconsistent even under the steady operation condition. In order to accurately evaluate the VRF system's dynamic energy performance, this study proposed a data-mining-based method to benchmark and assess its energy uses. The correlation analysis is used for key factors selection and the interquartile range rule is employed to remove outliers of the database. In addition, the power consumption patterns are classified using decision tree (DT) method. The classification results are validated by the ANOVA analysis and post hoc test. Nine energy benchmarks are established based on the classified power consumption patterns. Moreover, an energy consumption rating system is established to provide quantitative assessment on the power consumption of the VRF system. A case study is conducted by comparatively analyzing the energy performance of the VRF system at multiple refrigerant charge fault cases. Results show that both the PLR and OT significantly affected the power consumption of the VRF system. However, the degree to which the refrigerant charge fault affects system power consumption varies with the power consumption patterns. For different patterns, the power consumptions of the VRF system were either lower, higher or similar to each other at various RCLs. Results also suggest that the energy benchmarking process provide reasonable classification criteria, and the grading process provide quantitative assessment on the energy consumption. Therefore, the proposed dynamic energy benchmarks are reliable and reasonable to evaluate the dynamic energy performance of VRF systems.

1. Introduction

Building energy consumptions are the main focus of the world-wide energy policy nowadays, since they constitute 40% of total energy consumption as well as more than 30% of global greenhouse gas emissions [1]. The high level of building energy uses and the fast increasing of building energy demand push the technique innovation of building energy retrofit. For instance, application of photovoltaic generation technology, district cooling system in the newly designed buildings [2,3], and promotion of the *Display Energy Certificates (DECs)* or *Energy Star* for new and existing buildings to improve their energy performance [4,5]. Recently, as an energy-efficient candidate of the heating, ventilation and air-conditioning (HVAC) system, the variable refrigerant flow (VRF) system enjoys great popularity in both commercial and residential buildings. Previous researches suggested that the VRF system has lower energy dissipation than the common air conditioning system (e.g. variable air volume, fan-coil plus fresh air) under the same condition [6–8]. In addition, it has outstanding part-

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Nomenclature

A_{lk}	heat leakage area (m^2)
C_d	nozzle flow rate (m^3/s)
d_a	air humidity ratio (kg/kg dry air)
DT	decision tree
E_{actual}	energy consumption of the VRF system in a given condition
ER_{actual}	energy rating of the VRF system in a given condition
FL	full load
h_i	enthalpy of inlet air (J/kg)
h_o	enthalpy of outlet air (J/kg)
HL	half load
OT	outdoor temperature
PLR	part load ratio
q_a	air flow rate (m^3/s)
Q_{lk}	indoor heat leakage (W)
QL	quarter load
RCL	refrigerant charge level
T	temperature (°C)
va	specific volume of moist air (m^3/kg)
VRF	variable refrigerant flow
Xs	saturated air humidity ratio
ΔPn	pressure difference of the nozzle inlet side and outlet side (Pa)

Greek letters

α_{lk}	heat leakage coefficient (W/m^2 °C)

Subcripts or superscripts

a	atmosphere
db	dry-bulb
i	inlet air
in	indoor
n	front side of nozzle
o	outlet air
out	outdoor
sp	static pressure
wb	wet-bulb

load efficiency and can provide flexible thermal comfort control. Hence, numerous researches were conducted on improving the energy performance and promoting the application of VRF systems.

1.1. Studies on building VRF systems

Recent development of VRF systems are mainly focusing on numerical and experimental studies, steady-state or dynamic modeling researches, advanced control strategy exploitations, etc. [9,10]. A multitude of studies have attempted to improve the energy efficiency of VRF systems. According to related reviews in [9,10], previous investigations of VRF systems mainly includes four aspects: (1) simulation of the component and system [11–14]; (2) field performance tests on VRF systems [15–17]; (3) comparatively analysis on VRF systems and other HVAC systems [6–8]; (4) optimization of the control strategy of variable speed compressor and EXVs [18–20]. So far, however, there has been limited discussion about energy performance evaluation on VRF systems.

1.2. Challenges on evaluating the energy performance in VRF systems

Compared to other HVAC systems, the VRF system has different energy performance due to its multiple indoor units and variable refrigerant control strategies [9,21]. Firstly, different operational conditions of the indoor units (e.g. "ON" or "OFF" and different set-points) may lead to various part load ratios. As shown in Fig. 1 (a) (plotted using our experimental data), the boxplot illustrates the distributions of the heating capacity and power consumption at different part loads cases (i.e. different number of operating indoor unit). It was found that the energy performance of the VRF system was extremely different in various part load operation conditions. Previous studies of Laeun et al. [17] and Meng et al. [21] also emphasized the variation of both energy consumption and COP in different operation conditions. Secondly, in order to provide flexible zone comfort control, the VRF system adjusts the refrigerant flow via variable speed compressors and electronic expansion valves (EEVs). However, it gave rise to inconsistent power consumption even in the steady operation condition as illustrated in Fig. 1(b) (plotted using our experimental data). This was also demonstrated in Refs. [14,22].

Therefore, it poses a challenge on evaluating the dynamic energy performance of the VRF systems. Numerous efforts have been conducted to reduce the energy uses and improve the efficiency of VRF systems. However, very limited studies can be found in evaluating the energy performance of VRF systems. In other words, to make previous efforts effective, it is necessary to clearly assess the energy consumption

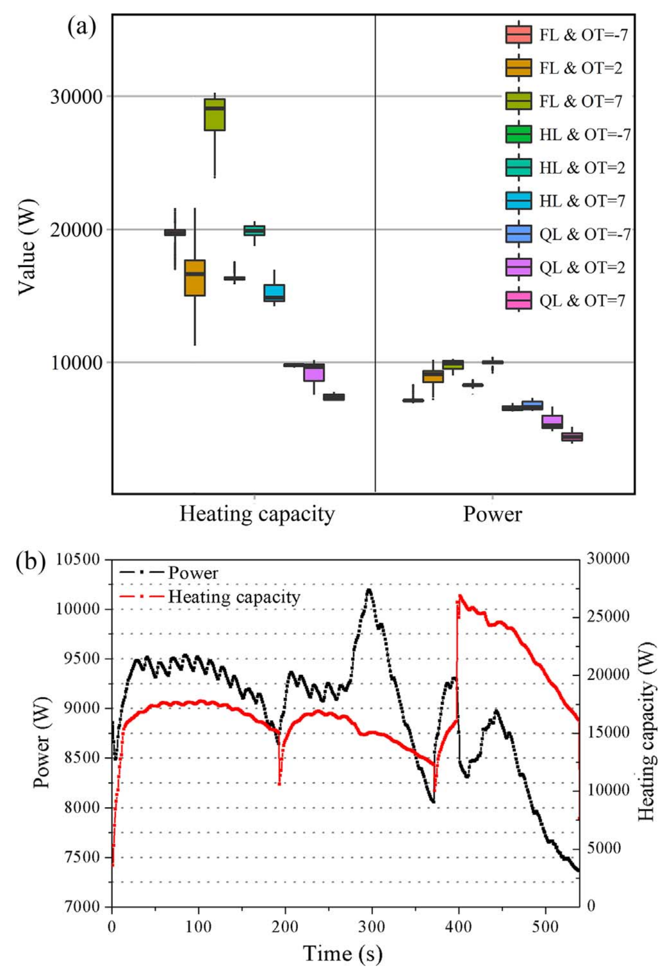

Fig. 1. Energy performance of VRF at different operation conditions. (a) Various PLRs and outdoor temperatures (The labels denote the operation conditions, e.g. FL & OT = −7 means full load and outdoor temperature of −7 °C); (b) full load and outdoor temperature of 2 °C.