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Field evaluation of advanced controls for the retrofit of packaged air conditioners and heat pumps

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HIGHLIGHTS

- An extensive field test of advanced controls for packaged rooftop air conditioner and heat pump unit retrofits.
- The controller can save more than 50% of packaged rooftop air conditioner and heat pump electricity.
- Supply-fan energy reduction contributes most of the RTU electricity savings.
- A generalized equation is provided to predict electricity savings.

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ABSTRACT

This paper documents the magnitude of energy savings achievable in the field by retrofitting existing packaged rooftop air conditioner and heat pump units (RTUs) with advanced control strategies not ordinarily used for RTUs. A total of 66 RTUs on 8 different buildings were retrofitted with a commercially available advanced controller for improving operational efficiency. The controller features enhanced air-side economizer control, multi-speed fan control, and demand-controlled ventilation. Of the 66 RTUs, 18 are packaged heat pumps and the rest are packaged air conditioners with gas heat. The eight buildings cover four building types and four climate conditions. Based on the performance data collected for approximately 1 year, the normalized annual energy consumption savings ranged between 22% and 90%, with an average of 57% for all RTUs. The average fractional savings uncertainty was 12% at 95% confidence level. Normalized annual electricity savings were in the range between 0.47 kW h/h (kW h per hour of RTU operation) and 7.21 kW h/h, with an average of 2.39 kW h/h. RTUs greater than 53 kW and runtime greater than 14 h per day had payback periods less than 3 years even at electricity price of $0.05/kW h.

1. Introduction

RTUs are factory-made, self-contained equipment comprising a number of off-the-shelf components available in standard design and cooling capacities. In the U.S., RTUs are used in 46% (2.1 million) of all commercial buildings, serving over 60% (3.6 billion m^2) of the commercial building floor space [1]. The site cooling energy consumption associated with RTUs is about $2.4 * 10^8$ GJ annually. Therefore, even a small improvement in the operational efficiency of these units can lead to significant reductions of national energy use and carbon emissions.

Most packaged units in the field use "standard" conventional control strategies. The compressor or gas furnace cycles on or off to maintain the space set point while the supply fan operates continuously at the design speed during occupied periods to meet the space ventilation requirement. Although many RTUs are equipped with economizer dampers, industry studies have shown that over 60% of them do not operate correctly [2]. It is common that the economizer control strategies in existing RTUs cannot take full advantage of outside air for free cooling. For example, all RTUs tested in this work used a fixed dry-bulb temperature as the high limit for economizer controls before they were retrofitted with the advanced controllers. Under this economizer control strategy, the outdoor-air damper is fully open when the outdoor-air temperature is less than 12.8 °C and the thermostat calls for cooling. Otherwise, the damper is set to its minimum position even if the outdoor air is beneficial to address cooling loads.

Many retrofit opportunities exist to improve the operational efficiency of packaged air conditioners. Criscione [3] reported that several add-on controllers are emerging for RTU retrofits. Simulation studies [4–6] were made previously to investigate the

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magnitude of energy and cost savings that can be achieved from advanced RTU controls. For example, simulation results from Wang et al. [6] showed that simply adding multi-speed supply-fan control and demand-controlled ventilation to packaged air conditioners leads to energy savings of between 14% and 42% and cost savings between 27% and 59% for 16 locations covering all 15 climate zones in the U.S. The savings could be even higher for packaged heat pumps [7]. However, except for simulation studies, there is little solid work to validate the magnitude of energy and cost savings that can be achieved from RTU control retrofits in the field. Sunde et al. [8] presented the results from a pilot field demonstration of an RTU retrofit technology (digi-RTU Optimizer) that utilizes one variable-frequency drive (VFD) to modulate both the supply fan and compressor speed of the RTU. Based on 24 RTUs in the service territory of Omaha Public Power District, the test data over a couple of months showed that the digi-RTU Optimizer technology can reduce the average peak electricity demand by 39% and annual electricity savings by 56%. Doebber et al. [9] tested the same RTU advanced controller as used in this paper. Performed in Hawaii, their tests included 9 RTUs in three buildings. Over the test period of three to six months, they found that the advanced controller achieved from 5% to 15% annual energy savings at the building level.

To enhance the confidence of the utilities and building owners to adopt the advanced RTU controls for retrofits, an extensive field test is needed to cover more climate conditions, RTU capacities, different building types, and robust uncertainty analysis. . This paper presents the major findings from the field test performed from 2012 to 2013. The results from this work are important for building owners and utility companies to evaluate the financial merits of existing RTU retrofits with advanced controllers.

2. Advanced RTU controller description

The advanced controller used in this field test was designed to convert existing constant-air-volume rooftop units to highly efficient single-zone and variable-air-volume units. Upgrading an RTU with the advanced controller involves installation of a VFD and several sensors. The advanced controller can operate in conjunction with existing thermostats or building automation system. The controller monitors the thermostat signals or building automation system commands for heating and cooling and modulates the supply-fan speed and outdoor-air damper opening. The advanced controller can also work as a stand-alone building management system. In this case, the controller uses space temperature sensor readings, heating and cooling temperature set points, and the occupancy schedule to generate control signals. The following subsection describes the strategies used in the advanced controller for integrated air-side economizers, sequence of cooling stages, supply-fan speed controls, and demand-controlled ventilation.

2.1. Integrated air-side economizer controls

The advanced controller provides integrated economizer control based on differential dry-bulb temperature or differential enthalpy. To realize the economizer control based on differential dry-bulb temperature, a temperature sensor needs to be mounted in the return-air duct. To realize the control based on differential enthalpy, additional relative humidity sensors are needed for the outdoor air (OA) and the return air. By full integration with the mechanical cooling system, the economizer can use 100% outdoor air to provide as much cooling as possible when the outdoor-air condition is favorable.

2.2. Sequence of cooling stages

When the space calls for cooling, the advanced controller uses the outdoor-air temperature as the trigger point to determine the unit's operation at different cooling stages. A cooling stage can be economizer only, economizer integrated with mechanical cooling, or mechanical cooling only. The controller has the following sequence of cooling stages:

- If the outdoor-air temperature is below the compressor lockout set point at 14.4 °C, the economizer is used for both the first and the second stage cooling but with different fan speeds.
- If the outdoor-air temperature lies in between 14.4 °C and 21.1 °C, the air-side economizer is used for the first stage of cooling and economizer integrated with the first stage compressor for the second stage of cooling.
- If the outdoor-air temperature is above 21.1 °C, the stages of compressor cooling are initiated corresponding to the call of cooling stages. In both stages, the air-side economizer is used together with mechanical cooling if the outdoor-air condition is favorable.

2.3. Supply-fan speed controls

Through the added VFD, the advanced controller modulates the supply-fan speeds based on the RTU primary operational modes including ventilation, heating, and cooling. The rooftop unit operates in the ventilation mode if (1) the sensed space temperature lies between the heating and cooling set points, and (2) the space is scheduled to be occupied. The heating operational mode is called on if the sensed space temperature is less than the heating set point. Once heating is initiated, it continues until the space temperature rises above the heating set point plus a differential. Similarly, the cooling operational mode is called on if the sensed space temperature is greater than the cooling set point. Once cooling is initiated, it continues until the space temperature decreases below the cooling set point minus a differential. Detailed discussions of these operation modes can be found in Wang et al. [6]. Table 1 lists the fan speeds at different operational modes. When the RTU operates in the ventilation mode, the supply fan runs at 40% of its design speed. In the cooling mode, the fan speed varies according to the outdoor-air temperature and the stage of cooling. In the heating mode, for RTUs with staged gas furnaces, the supply fan runs at 75% and 90%, respectively, for the first and the second heating stages. For heat pumps and RTUs with one single stage of gas heating, the supply fan runs at 90% of its design speed.

2.4. Demand-controlled ventilation (DCV)

The advanced controller uses the return-air CO_2 measurement as the trigger point to modulate the OA damper opening. If the measured CO_2 concentration is less than the CO_2 set point of 1000 ppm, the OA damper is modulated to the minimum position

Table 1
Supply-fan speed settings of the advanced RTU controller.

Operational mode		Outdoor air temperature (°C)	Fan speed (%)
Cooling	1st stage	<14.4 or >21.1	75
		$\geqslant 14.4$ and $\leqslant 21.1$	90
	2nd stage	Any	90
Heating	1st stage (furnace)	Any	75
	2nd stage (furnace)	Any	90
	heat pump	Any	90
Ventilation		Any	40