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Original Research Article

Investigations of life cycle climate performance and material life cycle assessment of packaged air conditioners for residential application

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ABSTRACT

A comprehensive investigation for life cycle climate performance (LCCP) and material life cycle assessment (LCA) is performed under various influencing factors for the packaged conditioners. The whole carbon dioxide equivalent (CO_2-eq.) emissions during an air conditioner's lifetime are evaluated from the LCCP aspect. Results indicate that the seasonal energy efficiency ratio (SEER) rating has a large influence on the emission variation, 13 SEER R410A has approximately a +3% CO_2-eq. emission increase when compared with the 13 SEER R22 in the area of Richmond, which is mainly caused by the direct emission of annual leakage of high GWP R410A. The efficient 14 SEER R410A unit depicts a 9% reduction. In general, as the climate is varied from cold to hot, the emissions are increased. Among the emission contributors, the energy consumption accounts for more than 70% of the total emissions, followed by annual refrigerant leakage. Parameter analysis reveals that the refrigerant recovery rate has a larger effect on the LCCP results than the cycle degradation coefficient, especially in the cold areas. In addition, the two capacity air conditioner product has approximately a 13% emission reduction due to the better load matching. Material LCA investigation shows that, in general, most of the material phase environmental performance is decreased in 14 SEER air conditioners. This is because the addition of aluminum from employing of the micro-channel heat exchanger. For a sustainable future, minimizing material use and CO_2-eq. emissions and maximizing energy efficiency should have been considered in its entirety.

Introduction

Sustainability has become an alarming concern by increasing the awareness that there are limits to the availability of non-renewable resources, and there is the rising energy demand, especially in the area of heating, ventilating, air-conditioning and refrigeration (HVAC&R). To achieve a more sustainable future for products in various applications, both the research institutes and industry are taking more efforts to evaluate the environmental burdens with various products. Based on the U.S. Department of Energy (US DOE) [1], appropriately 70% of the households make use of the central air-conditioning systems run by a conventional external condenser or a heat pump. Therefore, the heating or cooling systems/products in the buildings deserve the further investigation to achieve better environmental impact. From the environmentally life-cycle perspective, a manufacturer is usually further challenged with strict design requirements, such as long operational life, maximizing the energy efficiency, maximizing the recyclable content, and minimizing the material use and CO_2 emissions, etc., to provide the most competitive products for the application.

Currently there are limited studies regarding the in-depth environmental impact of residential buildings for cooling or heating systems/products. One study [2] was performed for the life-cycle energy, greenhouse gas emissions, and costs of a contemporary 2450 sq ft (228 m^3) U.S. residential home (the standard home, or SH). A functionally equivalent energy-efficient house (EEH) was modeled that incorporated 11 energy efficiency strategies. These strategies led to a dramatic reduction in the EEH total life-cycle energy; 6400 GJ for the EEH compared to 16,000 GJ for the SH. Life-cycle greenhouse gas emissions were 1010 metric tons CO_2 equivalent for an SH and 370 metric tons for an EEH. However, the estimated operating inputs such as the electricity for products are directly mapped into model sectors for calculation without considering various operating conditions under different climates for the air conditioners and heat pumps. A study by Heikkilä [3] compares the life cycle environmental impacts of two air-conditioning systems for an office building in Sweden. The difference in the form and source of the energy dominates the relative environmental effects of the systems. Another study

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Nomenclature

AHRI	air-conditioning, heating, and refrigeration institute	HVAC&R	heating, ventilating, air-conditioning and refrigeration
AP	acidification potential	LCCP	life cycle climate performance
COP	coefficient of performance	ODP	ozone depletion potential
EEH	energy efficient house	EOL	end of life
GHG	greenhouse gas	EP	eutrophication potential
SEER	seasonal energy efficiency ratio	LCA	life cycle assessment
SFP	smog formation potential	GWP	global warming potential

by Ochoa et al. [4] was conducted for the environmental impact for improving a single family house and outlined a simple approach to a life cycle analysis for residences. However, the following two studies did not consider the effect of climate for products as well, and this study by Ochoa et al. [4] was admitted their study was limited in the life cycle assessment to the building environmental impacts. There are many other similar studies. Therefore, based on the literature review, there are few, limited in scope, and fragmented investigations with in-depth analysis for the environmental impact including the climate effect for residential applications.

To reveal the in-depth analysis, some powerful and necessary tools evaluating the product environmental performance or impact are briefly introduced here. One tool for is the web-based interactive life cycle climate performance (LCCP) modeling program for residential heat pumps and air conditioners from reference [5]. LCCP is a methodology that is used to assess the total global warming potential (GWP) impacts (both direct and indirect emissions), expressed as carbon dioxide equivalent mass (kg-CO_2 eq.), over the lifetime of a particular refrigerant, piece of equipment or system with different climate inputs. It can be expressed as a summation of all sources of the direct and indirect source emissions. This tool has the detailed input parameters for the use phase, including various operating conditions based on ANSI/AHRI Standard 210/240 [6] with different climate conditions, cycle degradation coefficient, various cities, etc. It will calculate the equivalent mass of CO_2 released into the atmosphere for different air conditioner types. As mentioned before, there are few investigations that do a complete and comprehensive work with covering one product area in detail comparing various influencing parameters to achieve the lowest environmental impact. Therefore, in the current study, the LCCP investigation is performed comprehensively, from both the direct and indirect emission aspects for the packaged 14 SEER air conditioners. In addition, there is a lack of material life cycle assessment (LCA) analysis for the latest HVAC&R products based on the recent component update from various environmental impacts from the literature review. Here the Ingersoll Rand's (IR) Screening LCA tool, which is followed the ISO 14000 series standards [7–10], managed by PE, is used to evaluate the potential environmental impacts from the material phase.

Therefore, in the current study the LCCP is used efficiently to evaluate the environmental impact of the packaged air conditioners from a whole life cycle aspect, including both the direct and indirect emissions. LCA tool can be efficiently utilized for the material phase during the material production stage, which is a small part for the indirect emissions. To show more detail about the environmental impacts for material phase, it includes not only the GWP, but also the acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), and smog formation potential (SFP). The discoveries from the current study are beneficial for the researchers, engineers and manufactures to minimize the total environmental impact through maximum efficiency and maintaining the maximum sustainability and safety. It can be also beneficial for the researchers and engineers to design the more efficient and convenient environmental impact assessment tools.

Air conditioner unit performance

The system test conditions are shown in Table 1 [6].

The indoor unit capacity (Q) is determined using the mass flow rate (m_{air}) and the indoor air side enthalpy difference (Δh), as shown in Eq. (1). The COP is determined as the ratio of the indoor unit air capacity (Q) over the air conditioner total power (W) including both the compressor and fan power, as shown in Eq. (2).

$$Q = m_{air}\Delta h \quad (1)$$

$$\mathrm{COP} = Q/W \quad (2)$$

The COP (or the further calculated SEER) and capacity from cooling A are used for LCCP calculation, as shown in Figs. 1 and 2. Basically, there are three categories: 13 SEER R22, 13 SEER R410A and 14 SEER R410A. The 13 SEER R410A and 14 SEER R410A are the entry level Ingersoll Rand/Trane packaged air conditioner products. On April 24, 2014, the Department of Energy (DOE) and the American Public Gas Association (APGA) reached a settlement agreement on the implementation of the Federal Regional Standards [11]. From this new standard, in 2015, the U.S. DOE will increase the minimum federal standard for the air conditioners in the southern U.S. (including Arizona) to 14 rated seasonal energy efficiency ratio (SEER). The new standards are part of a compromise among industry groups and environmental and consumer advocates. This is resulting from a lawsuit brought against DOE by the Natural Resources Defense Council in 2004 after the Bush administration attempted to reverse air-conditioner efficiency standards set by the Clinton administration. Following this trend, the new 14 SEER R410A products are designed and released. As seen from Fig. 1, the cooling capacity for three categories is pretty close, while the total power consumption for the 14 SEER R410A is the lowest. As seen from Fig. 2, the 14 SEER R410A has the highest SEER value and the 14 SEER R410A in general has the slightly lower cycle degradation coefficients than the old 13 SEER R22 and 13 SEER R410A, which means for the most part it can achieve the better thermal performance than others.

Table 1
ANSI/AHRI standard 210/240 test matrix.

Test	Indoor		Outdoor		Operating
	D.B.	W.B.	D.B.	W.B.	
Extended condition	80 °F	67 °F	115 °F	NA	Steady state cooling
Cooling A	80 °F	67 °F	95 °F	NA	Steady state cooling
Cooling B	80 °F	67 °F	82 °F	NA	Steady state cooling
Cooling C	80 °F	⩽57 °F	82 °F	NA	Steady state cooling, dry coil
Cooling D	80 °F	⩽57 °F	82 °F	NA	Cyclic cooling, dry coil