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Comparison of environmental impacts of two residential heating systems

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Abstract

This paper presents a comparison of environmental impacts of two residential heating systems, a hot water heating (HWH) system with mechanical ventilation and a forced air heating (FAH) system. These two systems are designed for a house recently built near Montreal, Canada. The comparison is made with respect to the life-cycle energy use, the life-cycle greenhouse gas (GHG) emissions, the expanded cumulative exergy consumption (ECExC), the energy and exergy efficiencies, and the life-cycle cost. The results indicate that the heating systems cause marginal impacts compared with the entire house in the pre-operating phase. In the operating phase, on the other hand, they cause significant environmental impacts. The HWH systems with a heat recovery ventilator (HRV) using either electricity or natural gas have the lowest life-cycle energy use and lowest ECExC. The HWH and FAH systems using electricity as energy source have the lowest GHG emissions. Finally, the FAH systems have, on the average, a lower life-cycle cost than the HWH systems.

Keywords: Environmental impacts; Heating systems; Hot water heating; Forced air heating; House; Life-cycle analysis; Energy; Exergy; Emissions; Cost

1. Introduction

Residential and commercial/institutional buildings contribute to more than 30% of the secondary energy use and greenhouse gas (GHG) emissions in Canada [1], with a significant impact on the environment. The assessment of environmental impacts of buildings should cover a large number of indicators from several domains such as engineering, architecture, ecology, social sciences and health, economic and demographic growth. A large-scale multi-disciplinary optimization problem should be solved to design and operate buildings having the minimum environmental impacts. Currently, several approaches have been developed within each domain using a number of practical indicators to express the environmental impacts.

Most papers published so far in the engineering domain have focused on the impact of exterior envelope and structural system on the life cycle of buildings, using as indicators energy, emissions, and cost. Only a few papers discussed the environmental impacts of heating, ventilating and air-conditioning (HVAC) systems. This research project contributes to the HVAC area by focusing on the environmental impacts of two residential heating systems, a hot water heating (HWH) system with mechanical ventilation and a forced air heating (FAH) system [2]. The paper presents an engineering approach where the environmental impacts are evaluated by estimating the life-cycle energy use, the life-cycle expanded cumulative exergy consumption (ECExC), the energy and exergy efficiencies that can reflect the depletion of natural resources, and the life-cycle GHG gas emissions that can reflect the pollution of outdoor environment. The life-cycle cost is included to reflect the current economic impact due to the installation and operation of HVAC systems.

The paper is organized as follows. The next section presents a literature survey of related published research in evaluating the environmental impacts of buildings. The third section presents the design of the two heating systems.

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This is followed by an analysis of the environmental impacts at the pre-operation phase (fourth section) and the annual operation phase (fifth section). The results of the previous two phases are combined in the sixth section with a life-cycle analysis. The paper ends with some concluding remarks and suggestions for future work.

2. Previous studies on the environmental impacts of houses

Several studies have investigated embodied energy vs operating energy in houses. Mumma [3] estimated that the embodied energy of a 350 m^2 ranch-style house in Canada is equal to 7 yr of annual operation energy use in the case of a conventional house and 18 yr in the case of an energy efficient house. Adalberth [4] estimated the life-cycle energy use of three single-unit dwellings built in Sweden. The embodied energy of construction materials is between 2630 and 3240 MJ/m^2 of floor area, and accounts for 10% of the total energy use over 50 yr. The operation energy use is between 23,040 MJ and 26,640 MJ/m^2, and accounts for 85% of the total life-cycle energy use. The total embodied energy corresponds to about 7 yr of operation energy use for space heating, hot water, and appliances. Kassab [5] presented the life-cycle analysis of a recent energy efficient residential house in Montreal, Canada, of 310 m^2 floor area. The embodied energy of the exterior envelope and structural system was estimated at 2280 MJ/m^2. The embodied energy equals about 19 yr of annual heating energy use. The life-cycle GHG emissions were estimated at 67.1 ton of equivalent CO_2. Mithraratne and Vale [6] evaluated the embodied energy of a 94 m^2 typical residential house, built with a softwood frame structure in Auckland, New Zealand, at 4700 MJ/m^2 and the annual space heating energy use at 83 MJ/m^2. The embodied energy equals about 57 yr of heating energy use. Blanchard and Reppe [7] presented the life-cycle analysis of a residential house of 230 m^2 floor area built in Ann Arbor, MI, which included the exterior envelope and structural system, and the electrical, plumbing, and heating systems. The embodied energy was estimated at 4100 MJ/m^2 or 6.1% of total life-cycle energy use (for a life of 50 yr), while the operation energy use was 63,000 MJ/m^2 (93.7%), and the energy use for demolition was 31 MJ. The mass inventory revealed the use of 3720 kg of steel, mostly used for duct system, appliances, and fasteners, with the corresponding embodied energy of 121 GJ and GHG emissions of 8700 kg.

The values presented above for the embodied energy in houses vary significantly between 2280 and 4700 MJ/m^2 of floor area. These differences arise from the different climate and locations considered. However, data from two houses located in different climates, most likely with different requirements from an energy-related stand point: Auckland, New Zealand [6], and Ann Arbor, USA [7], show quite similar embodied energy values: 4700 vs 4100 MJ/m^2. The impact of climatic conditions is revealed indirectly, for these two cases, by the equivalent number of years of annual operation energy use required to equate the embodied energy: in a warm climate it is about 57 yr [6], while it is only 15 yr in a cold climate [7].

Only a few studies found focused on HVAC systems. Legarth et al. [8] analyzed the environmental impacts of an air-conditioning unit using nine impact categories (such as global warming and ozone depletion), four waste categories, and nine natural resource categories. A study reported by the Canadian Mortgage and Housing Corporation [9] focused on a new multi-unit residential building located in Ottawa that has a concrete structure with steel stud/brick exterior walls. The embodied energy of the mechanical systems accounted for 13% of both initial embodied energy and life-cycle embodied energy. Treloar et al. [10] analyzed an energy efficient two-story residential house of 115 m^2, including the structural system, space heaters, solar hot water service, and external elements such as paving and pergolas. The embodied energy was estimated at 11,100 MJ/m^2, including 870 MJ/m^2 for the construction process. Prek [11] evaluated the environmental impact of manufacturing process of three residential heating systems of 11.8 kW output: a radiator heating system with metal pipes, a floor heating system with polyethylene pipes, and a fan coil convector heating system. The heat conversion equipment and fittings were not taken into account. The study used the Eco-indicator 95 method to aggregate various environmental impacts into one single indicator. The radiator heating system was found to have the highest environmental impact while the floor heating system has the lowest environmental impact. Heikkilä [12] evaluated the environmental impact of two air-conditioning units of a capacity of 4.8 m^3/s, using the weighting method EPS 2000. The first unit has a cooling coil with a vapor compression chiller, while the second unit uses a desiccant cooling device. The second system has a higher environmental impact than the first system due to the larger amount of thermal energy used for annual operation. They found that the copper and steel have the highest contribution to the environmental impact during the manufacturing process. Ardente et al. [13] estimated the embodied energy of a solar thermal collector at 11 GJ; however, they estimated uncertainties to $\pm 20\%$. Equivalent CO_2 emissions due to the manufacturing of solar collector were estimated at 700 kg CO_2; however, they may vary by $\pm 17\%$.

Over the past three decades, the concept of exergy and entropy has been adopted to evaluate the environmental impact of buildings and the depletion of natural resources by a number of researchers (e.g., [14–20]). Cornelissen [21] stated that all environmental effects associated with emissions and depletion of natural resources can be expressed by one indicator, which is based on physical principles. He presented the exergetic life-cycle analysis of three district heating systems, and also defined the rational efficiency of a heat exchanger, based on the second law of thermodynamics. Zhang and Reistad [22] proposed a method to calculate the total equivalent resource exergy