Energy 53 (2013) 332–342

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Application of entransy in the analysis of HVAC systems in buildings

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ARTICLE INFO

Article history:
Received 4 December 2012
Received in revised form
31 January 2013
Accepted 8 February 2013
Available online 6 March 2013

Keywords:
HVAC systems
Energy efficiency
Entransy analysis
Indoor cooling

ABSTRACT

The main task of HVAC systems in the cooling condition is to remove heat from indoor environment to outdoor environment. HVAC systems are complex networks of various processes, e.g., heat transfer, heat–work conversion, heat–humidity conversion, etc. These processes correspond to equipment such as heat exchangers, indoor cooling terminals, heat pumps, and cooling towers. Single analysis method or thermal parameter could hardly describe all the processes in an HVAC system. Exergy destruction refers to the loss of heat–work conversion ability. Reducing exergy destruction indicates less supplied exergy (input work) of HVAC systems. Entransy is a new parameter defined as heat transfer ability. Entransy dissipation refers to the loss of heat transfer ability. When the purpose of heat transfer is cooling or heating, entransy analysis is a direct method for optimizing heat transfer processes. Loss of HVAC system is mainly in heat transfer process. The entransy dissipation extremum principle or the minimum thermal resistance principle is suitable for analyzing heat transfer process in HVAC system. For indoor cooling, reducing entransy dissipation will increase chilled water temperature. Flow unmatched coefficient ξ represents an increase of thermal resistance of heat exchanger if the calorific capacities of the fluids are different.

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems are used to create suitable indoor environments, but they account for a large proportion of the energy use of buildings. Due to worldwide energy shortages and rising living standards, a more efficient utilization of energy in HVAC systems is desirable. Increasing attention is being given to thermodynamic analysis of HVAC systems based on two fundamental natural laws, known as the first and second laws of thermodynamics.

The first law of thermodynamics is expressed as the conservation of energy. In HVAC systems, reducing cooling/heating loads is the primary way to save energy. The second law of thermodynamics asserts that energy has quality as well as quantity. Exergy represents the "work potential" of energy, and is an essential tool for the design, analysis, and optimization of thermal systems [1]. On the system level, two international cooperative agreements that use exergy to study heating and cooling in buildings have been advanced by the International Energy Agency (IEA): Energy Conservation in Buildings and Community Systems (ECBCS) Annex 37 and Annex 49. Based on the idea of low exergy systems, Annex 37 [2] promotes the rational use of energy by facilitating and accelerating the use of low-valued and environmentally sustainable energy sources. Annex 49 [3] uses exergy analysis as a basis for providing tools, guidelines, recommendations, best practice examples, and background information to designers and decision-makers. Alpuche et al. [4] applied the exergy method to air cooling systems in buildings located in hot and humid climates. Akpinar et al. [5] conducted an exergetic performance evaluation of two types of geothermal heat pump systems; the exergy (second law) efficiency was given for both systems, and the exergy destruction in each system component was determined in order to assess individual system performance. Yildiz and Gungor [6] performed energy and exergy analysis for the whole process of space heating in buildings; energy and exergy flows were investigated, and energy and exergy losses in the whole system were quantified and illustrated.

Second law analysis and exergy analysis have been used to study components of HVAC systems, such as heat exchangers, cooling towers, and air handling units. Hesselgreaves [7] reviewed various approaches to second law analysis of heat exchangers and provided a rational method for resolving the "entropy generation paradox." Qureshi et al. [8] presented a second law-based evaluation of cooling towers and evaporative heat exchangers under varying operating conditions. Exergy analysis has also been applied to liquid and solid desiccant dehumidification systems: Xiong et al. [9]

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http://dx.doi.org/10.1016/j.energy.2013.02.015

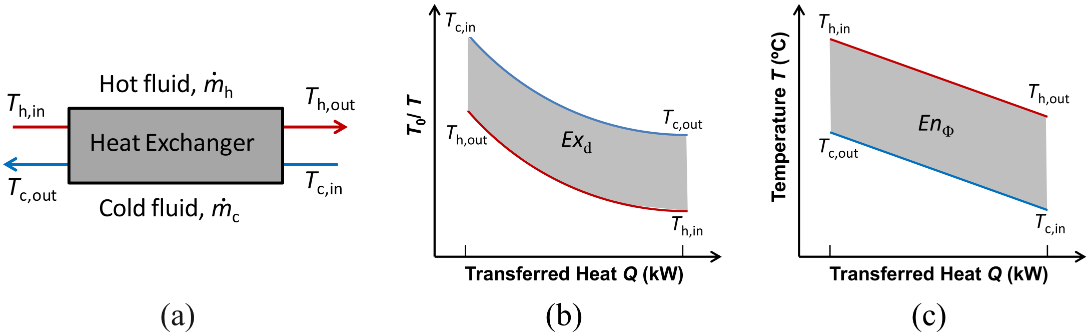

Fig. 1. A counter-flow heat exchanger.

improved a liquid desiccant dehumidification system from the perspective of exergy analysis, and Kanoglu et al. [10] derived exergy destruction and exergy efficiency relations for an open-cycle desiccant cooling system.

These studies mainly focus on the second law of thermodynamics, but heat transfer is another important aspect of HVAC systems. Guo et al. [11] introduced the new physical parameter known as entransy, or heat transfer ability. Based on this parameter, entransy dissipation and equivalent thermal resistance were introduced [12]. During heat transfer processes, entransy is not conserved due to dissipation caused by thermal resistance, while the thermal energy is conserved. Entransy is a useful tool for optimizing heat transfer processes. The entransy dissipation extremum principle was applied to optimize the volume-to-point access thermal conduction problem [11]. Heat exchangers are the most common components of HVAC systems. The equivalent thermal resistance of heat exchangers was defined by Guo et al. [12], which measures the irreversibility of heat transfer. Chen et al. [13] studied the equivalent thermal resistance of a heat exchanger couple. Shan et al. [14] propose a three-step strategy to optimize geometries of various self-similar transport networks based on the entransy theory. The transport network was optimized if the entransy dissipation rate was minimized, and equipartition law for optimizing transport networks can be derived [15]. Other components of HVAC systems, such as evaporative cooling system and building central chilled water systems, have been examined as well [16,17].

HVAC systems are complex networks of various processes, e.g., heat transfer, heat–work conversion, heat–humidity conversion, etc. These processes correspond to equipment such as heat exchangers, indoor cooling terminals, heat pumps, and cooling towers. Single analysis method or thermal parameter could hardly describe all the processes in an HVAC system. This study examines HVAC systems based on the second law of thermodynamics and heat transfer processes, and applies exergy and entransy analysis to HVAC systems in buildings. Exergy refers to heat–work conversion ability, which is a suitable parameter for optimizing the input work of the system. Entransy is defined as heat transfer ability, which represents a new perspective with regard to heat transfer processes in HVAC systems.

2. Basic definition

2.1. Basic definition of exergy

In HVAC systems, total exergy is the sum of physical (thermomechanical) exergy and chemical exergy. For example, the total exergy flow rate of humid air in standard atmospheric pressure is calculated by Eq. (1), where the first term is the physical exergy and the second term is the chemical exergy [18]:

$$\begin{aligned}\dot{E}x(T,\omega) = {} & \dot{m}_a c_{p,h} T_0\left(\frac{T}{T_0}-1-\ln\frac{T}{T_0}\right) \\ & + \dot{m}_a R_a T_0\left((1+1.608\omega)\ln\frac{1+1.608\omega_0}{1+1.608\omega}\right. \\ & \left. + 1.608\omega\ln\frac{\omega}{\omega_0}\right)\end{aligned} \tag{1}$$

The purpose of HVAC systems is to maintain suitable indoor temperature and humidity; in other words, the objective of the thermodynamic system is certain. Based on entropy generation equation and Gouy–Stodola theorem, the balance equation of exergy flow rate in HVAC systems can be written as follows:

$$\dot{E}x_s - \dot{E}x_d = \dot{E}x_o \tag{2}$$

The supplied exergy flow rate ($\dot{E}x_s$) can be heat or cooling, dry or humid air, the input work of the heat pump, etc. The destroyed exergy flow rate ($\dot{E}x_d$) indicates the irreversibility of the system. For a certain obtained exergy flow rate ($\dot{E}x_o$), reducing destroyed exergy flow rate in the system results in less supplied exergy flow rate. For a counter-flow heat exchanger as shown in Fig. 1, the exergy flow rate of fluid is:

$$\dot{E}x = \int_{T}^{T_0} \dot{m}c_p\left(1-\frac{T_0}{T}\right)\mathrm{d}T \tag{3}$$

The destroyed exergy flow rate in heat transfer process is Eq. (4), which can be depicted by Fig. 1(b).

$$\dot{E}x_d = \int_{0}^{Q}\left(\frac{T_0}{T_c}-\frac{T_0}{T_h}\right)\mathrm{d}Q \tag{4}$$

In the T_0/T–Q diagram, the two lines are not straight. The area between the two lines illustrates exergy destruction, which indicates the loss of heat–work conversion ability.

2.2. Basic definition of entransy

The idea of entransy comes from an analogy between heat conduction and electric conduction [11]; entransy corresponds to electric potential. The definition of entransy is based on the heat conduction equation, which is also the basis of entransy analysis. For heat conduction problems with inner heat source, the thermal energy conservation equation is