Energy and Buildings 67 (2013) 387–391

Contents lists available at ScienceDirect

Energy and Buildings

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

Analyses and optimizations of thermodynamic performance of an air conditioning system for room heating

XueTao Cheng, XinGang Liang *

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 22 November 2012
Received in revised form 18 July 2013
Accepted 18 August 2013

Keywords:
Air conditioning system
Thermodynamic performance
Entropy generation
Entransy loss
Optimization

ABSTRACT

This paper presents the optimization of an air conditioning system, in which the heat from the hot stream is transported to do work first, and then the work is used to pump heat from the environment into the room. It is shown that the system can deliver more heat into the room than the direct heating by the hot stream. A functional is set up to optimize the distribution of the total thermal conductance for the system, and the numerical results show that the functional is effective. The system is also discussed with the concepts of entropy and entransy. It is found that the minimum values of the entropy generation rate, entropy generation number, revised entropy generation number, entransy loss and entransy loss coefficient all correspond to the maximum heat flow rate into the room with prescribed heat flow rate from the hot stream, but the values of the parameters all increase with increasing heat flow rate from the hot stream and that into the room.

1. Introduction

Thermal problems in buildings attract the attention of researchers [1–5] because of the building energy conservation and the reduction in the cost. Researchers have done much work on the analyses and optimizations of air conditioning systems in recent years [2,3,6–8] due to their wide application in buildings. For different optimization objectives, different methods have been used [6–8]. For instance, Yao and Chen [6] used the method of decomposition–coordination to solve their global optimization model for the overall control of air-conditioning system, aiming at the minimum energy consumption. Parameshwaran et al. [8] investigated the genetic fuzzy optimization method to analyze the combined effect of the energy conservative variable refrigerant volume system and the variable air volume system.

In any air conditioning system, there are many irreversible thermodynamic processes. The entropy generation minimization method [9–13] is often applied. However, there are different viewpoints for the applicability of the entropy generation minimization to thermal systems. For heat exchangers, it was found that the entropy generation minimization does not always lead to the best performance [12,14–16]. For the refrigeration system, minimizing the entropy generation rate does not always result in the same design as maximizing the system performance unless the refrigeration capacity is fixed [17].

In the last decade, the entransy theory was developed for heat transfer optimization [18]. Based on the new concept, the entransy decrease principle [18], the extremum entransy dissipation principle [19] and the minimum entransy-dissipation-based thermal resistance principle [18] were developed and applied to the analyses and optimizations of many heat transfer processes [14–16,18–24], including the district heating networks in buildings [25]. Furthermore, the entransy theory has been extended to the analyses and optimizations of heat–work conversion systems [26–30]. Cheng et al. [26–30] proposed the concept of entransy loss and found that the increase in entransy loss rate is in accordance to the increase in output power for the discussed cases. However, there are not many researches on the applicability of the entransy theory to the air conditioning systems.

This paper mainly focuses on the thermodynamic performance of the air conditioning system. An air conditioning system for room heating is discussed. The heat from the hot stream is not used to warm the room directly, but is transferred to do work first and then the work is used to pump heat into the room from the environment. Considering that the investigations about the applicability of the concepts of entropy and entransy are necessary, we also analyze the system with the two concepts.

2. Theoretical analyses

The sketch of the discussed air conditioning system for room heating and the thermodynamic processes in the system are shown in Figs. 1 and 2, respectively. The prescribed heat flow rate into the system, Q_H, is supplied by the hot stream with a prescribed heat

* Corresponding author. Tel.: +86 10 62788702; fax: +86 10 62788702.
E-mail address: liangxg@tsinghua.edu.cn (X.G. Liang).

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http://dx.doi.org/10.1016/j.enbuild.2013.08.034

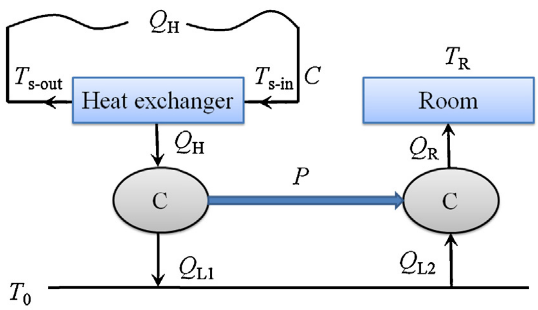

Fig. 1. A sketch of an air conditioning system for heating room.

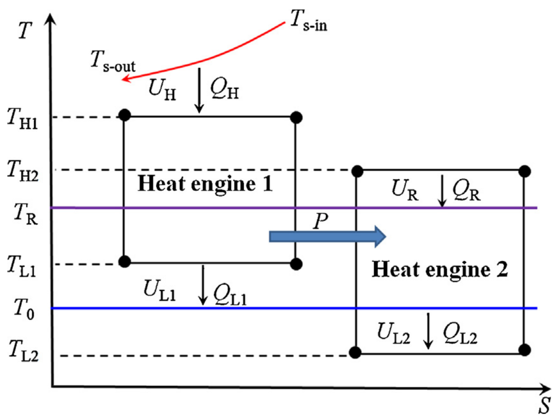

Fig. 2. *T–S* diagram of the air conditioning system for room heating.

capacity flow rate, C, and inlet and outlet temperatures $T_{s\text{-in}}$ and $T_{s\text{-out}}$, respectively. The heat flow rate Q_H is not directly delivered into the room, but is transferred to the working fluid of a Carnot cycle at temperature T_{H1} through a heat exchanger with a thermal conductance U_H for doing work. The working fluid releases heat flow rate Q_{L1} at temperature T_{L1} to the environment at temperature T_0 through a heat exchanger with a heat conductance U_{L1}, and power P is output from the first Carnot cycle. Then, P drives a reverse Carnot cycle to pump heat Q_{L2} from the environment into the room at temperature T_R through a heat exchanger with thermal conductance U_{L2}. The lower and higher temperatures of the reversed Carnot cycle are T_{L2}, T_{H2}, respectively. The reversed cycle releases a heat Q_R into the room from the working fluid at temperature T_{H2} through a heat exchanger with a thermal conductance U_R.

Considering the limited cost, we can assume that the total thermal conductance of the heat exchangers is a constant,

$$U = U_H + U_{L1} + U_R + U_{L2} = \text{const}, \tag{1}$$

where U is the total thermal conductance. The distribution of the thermal conductance should be optimized to increase the heat flow rate into the room as more as possible. To solve this optimization problem, let us analyze the system below.

For the system, the first law of thermodynamics gives

$$Q_R = Q_H + Q_{L2} - Q_{L1} = Q_H + (Q_{L2} - Q_{L1}) = Q_H + Q_L, \tag{2}$$

where Q_L is the net heat flow rate from the environment. It can be seen that Q_R is larger than Q_H when Q_L is positive, and we may deliver more heat into the room by using the system in Figs. 1 and 2 than by putting Q_H into the room directly.

The heat transfer rate between the hot stream and the working fluid of the Carnot cycle is [26]

$$Q_H = C(T_{s\text{-in}} - T_{H1})\left[1 - \exp\left(\frac{-U_H}{C}\right)\right]. \tag{3}$$

The heat transfer rate between the environment and the working fluid of the Carnot cycle is

$$Q_{L1} = U_{L1}(T_{L1} - T_0). \tag{4}$$

The Carnot theorem gives

$$\frac{Q_{L1}}{Q_H} = \frac{T_{L1}}{T_{H1}}. \tag{5}$$

The energy conservation leads to

$$Q_H = Q_{L1} + P. \tag{6}$$

From Eq. (3), we can get

$$T_{H1} = T_{s\text{-in}} - \frac{Q_H}{C\left[1 - \exp(-U_H/C)\right]}. \tag{7}$$

Substituting Eq. (7) into Eq. (5) yields

$$T_{L1} = T_{H1}\frac{Q_{L1}}{Q_H} = \frac{Q_{L1}}{Q_H}\left\{T_{s\text{-in}} - \frac{Q_H}{C\left[1 - \exp\left(-U_H/C\right)\right]}\right\}. \tag{8}$$

Substituting Eq. (8) into Eq. (4) leads to

$$Q_{L1} = \frac{T_0}{-1/U_{L1} + \left[T_{s\text{-in}} - (Q_H/C)/(1 - \exp(-U_H/C))\right]/Q_H}. \tag{9}$$

Considering Eq. (6), the output power of the first cycle can be expressed by

$$P = Q_H - Q_{L1} = Q_H - \frac{T_0}{-1/U_{L1} + \left[T_{s\text{-in}} - (Q_H/C)/(1 - \exp(-U_H/C))\right]/Q_H}. \tag{10}$$

For the reversed Carnot cycle, the heat transfer rates between the working fluid and the room and that between the working fluid and the environment are

$$Q_R = U_R(T_{H2} - T_R), \tag{11}$$

$$Q_{L2} = U_{L2}(T_0 - T_{L2}). \tag{12}$$

According to the Carnot theorem and energy conservation,

$$\frac{Q_{L2}}{Q_R} = \frac{T_{L2}}{T_{H2}}. \tag{13}$$

$$Q_R = Q_{L2} + P. \tag{14}$$

Combining Eqs. (12) and (13) leads to

$$Q_{L2} = \frac{T_0}{(1/U_{L2} + T_{H2}/Q_R)}. \tag{15}$$

Substituting Eq. (15) into Eq. (14) gives

$$T_{H2} = Q_R\left[\frac{T_0}{(Q_R - P)} - \frac{1}{U_{L2}}\right]. \tag{16}$$

Then from Eq. (11), there is

$$\frac{Q_R}{U_R} = Q_R\left[\frac{T_0}{(Q_R - P)} - \frac{1}{U_{L2}}\right] - T_R. \tag{17}$$

Considering Eq. (10), we have

$$\frac{T_0}{Q_R - Q_H - \left\{T_0/\left[(-1/U_{L1}) + [T_{s\text{-in}} - (Q_H/C)/(1 - \exp(-U_H/C))]/Q_H\right]\right\}} - \frac{1}{U_{L2}} - \frac{1}{U_R} - \frac{T_R}{Q_R} = 0. \tag{18}$$