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Performance investigation of terminal handling process in air-conditioning system from the perspective of entransy dissipation

Tao Zhang [a,b,*], Xiaohua Liu [a], Xiangjian Xiang [a], Jun Liu [a], Yi Jiang [a]

[a] Department of Building Science, Tsinghua University, Beijing 100084, China
[b] School of Aerospace, Tsinghua University, Beijing 100084, China

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ABSTRACT

Reducing the energy consumption of the air-conditioning system is of significant importance for building energy conversation. Removing indoor heat and moisture by terminal device is a basic component of the air-conditioning system. In the present study characteristics of this terminal handling process are investigated from the perspective of entransy dissipation. Characteristics of indoor heat sources are firstly clarified in terms of the temperature and heat flux. Depiction of entransy dissipation and objectives of this terminal handling process are then researched. Influences of mixing processes are quantified taking both Q and T into account. There are mainly two objectives for optimizing the heat collecting process: reducing the transferred heat Q from heat sources and increasing the required temperature of cooling source T_C. Case studies are carried out based on entransy dissipation analysis. Principles for improving the performance of terminal handling process are then proposed and discussed. It's indicated that adopting THIC system and avoiding mixing processes are two main approaches for an optimized indoor terminal process. The present analysis is beneficial to construct an energy efficient indoor terminal process and realize performance optimization of the entire air-conditioning system.

1. Introduction

In China, energy are mainly consumed by buildings, industry and transportation. It's urgent to reduce the energy consumption in buildings, which will be of great importance for the emission-reduction. Nowadays energy consumption of buildings accounts for an increasing proportion of the total energy consumption, about 20% in China [1]. In buildings, the air-conditioning system which is responsible for both heating and cooling usually consumes about 30%–60% [1,2] of the total building energy. Reducing the energy consumption of the air-conditioning system is one of the main aspects to achieve building energy-saving.

The air-conditioning system is composed of several key components, which could be classified as the heating/cooling sources, the transportation devices, the air handling process and the terminal handling process shown as Fig. 1 [3]. In the terminal handling process, intermediate media such as water or refrigerant is distributed from the sources with the help of transportation devices. Heat or mass transfer process occurs in the terminal device and indoor cooling required is satisfied. It's to say that the terminal handling process is just responsible for collecting indoor extra heat or moisture and removing it from indoor space to an appropriate sink [4]. Terminal handling process is regarded as the basis to construct an appropriate air-conditioning system and improving its performance is of great importance for the optimization of the entire system.

Terminal devices are also important topics in improving the performance of an air-conditioning system. The selection of an appropriate terminal device is a key issue in constructing the terminal handling process. Currently there have been plenty of researches focusing on the characteristics of common terminal devices including fan coil unit (FCU), radiant terminal and so on [5–7]. For example, thermal comfort, pressure drop and heat transfer properties of a FCU were investigated by Chu et al. [6] and Fernández-Seara et al. [7]. Radiant terminal is supposed to be a kind of terminal device with superiority in thermal comfort and energy performance. It is becoming more and more popular in recent years and increasing attentions have been paid into the characteristics of radiant terminals [8–12]. Li et al. [10] evaluated the performance of a low-energy building with radiant terminal in relation to its cooling capacity and thermal comfort. Heat transfer coefficient from water to room was tested as well as the heat loss through radiant panels. Steady-state simulations were carried out by Le Dréau

* Corresponding author at: Department of Building Science, Tsinghua University, Beijing 100084, China.
E-mail address: zt2015@mail.tsinghua.edu.cn (T. Zhang).

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Nomenclature

AUST	Average unheated/uncooled surface temperature (°C)
c_p	Specific heat capacity (kJ/kg °C)
ΔE_n	Entransy dissipation (kW K)
h	Enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
NTU	Number of transfer unit (dimensionless)
Q (q)	Heat flux (kW)
r	Indoor exhaust air
R	Equivalent thermal resistance based on entransy dissipation (K/W)
T	Absolute temperature (K)
T_r	Indoor air temperature (°C)
t	Temperature (°C)
ΔT	Temperature difference (°C)
$\Delta\overline{T}$	Equivalent temperature difference (°C)

Greek symbols

α	Convective heat transfer coefficient, W/(K m^2)
ω	Humidity ratio (kg/kg)

Subscripts

c	Cooling source
con	Heat convection
dis	Entransy dissipation
H	Heat transfer process
h	Heat source
lr	Longwave radiation
mix	Mixing process
Q	Heat source with constant heat flux
rs	Surface of radiant terminal
s	Surface of heat source or indoor floor
sa	Supply air
sr	Direct solar radiation
T	Heat source with constant temperature
w	Water

et al. [12] to characterize the advantages and drawbacks of different terminal devices. It was found that the cooling discrepancies between radiant terminal and convective terminal were mostly influenced by the air change rate, the outdoor temperature and the air temperature stratification.

On the other hand, the current increase of the energy consumption in buildings requires novel approaches or novel perspectives to clarify the essence of the terminal handling process. Thermological analysis using thermodynamic parameters such as entropy or exergy is an important approach [13]. Different from the conventional perspective only with emphasis on heating/cooling capacity Q, temperature level T or temperature difference ΔT is focused on as well as Q. Attracted by the superiority in providing theoretical guidance, continuous efforts have been paid in the exergy or entropy analysis of terminal devices or the entire air-conditioning system [14–17]. A radiant terminal combined with a convective terminal was investigated [16], which succeeded in achieving a low exergy terminal handling process. Recently the application of entransy, a new thermological parameter focusing on the transfer ability, is also attracting more and more attention [18–21]. Entransy dissipation and equivalent thermal resistance provide a novel perspective to investigate the transfer process. There have been investigations adopting entransy as the theoretical tool on heat exchanger [19], coupled heat and mass transfer processes [21] and so on. It's indicated that entransy analysis helps to cast light on the essence of the heat transfer process. However, the detailed entransy analysis on the terminal handling process of the air-conditioning system is still lacked. Besides, high temperature cooling system is attracting more and more attentions [22,23] with superiorities in both indoor environment and energy performance. Increasing the temperature of cooling sources creates favorable conditions for a wider use of natural cooling sources and improving the efficiency of the mechanical cooling sources. Then how to reduce the temperature difference consumed in the terminal handling process is also an important topic for achieving high temperature cooling.

Existing studies mainly focus on the terminals' performances to satisfy indoor requirements of cooling capacity or the appropriate selection of terminal devices. However there has been seldom analysis on the terminal handling component from a perspective of heat or mass transfer process, which is an important issue to understand the essence of the air-conditioning system. In the present study, characteristics of indoor heat and moisture sources are firstly clarified in terms of the temperature levels. Performance of the terminal handling process will be investigated with emphasis on the transfer characteristics, with the help of entransy dissipation. It is expected that the present analysis will be beneficial to the construction and optimization of the air-conditioning system.

2. Characteristics of heat and moisture sources

2.1. Types and temperature levels of heat sources

There are various types of indoor heat and moisture sources, such as building envelopes, occupants, equipment, and solar radiation. The space and temperature distributions of heat sources are quite nonuniform. Fig. 2 shows the measured temperature levels of typical indoor heat sources. It can be seen that the temperature levels of inner surfaces of building envelopes and indoor equipment are different. Table 1 lists the temperature levels of typical indoor heat sources. It can be seen that the sources' temperatures are relatively high, and some are even higher than the outdoor temperature, which is regarded as a heat sink. Cooling sources' temperatures required for removing heat depend on the temperatures of heat sources. The design outdoor temperature for most cities in China during summer is about 35 °C; the temperature of lighting device, as described in Table 1, is over 40 °C. Thus, outdoor natural cooling sources can be used for removing heat from indoor heat sources in theory.

In terms of whether their capacities are influenced by the environment, indoor heat sources can be clarified into two categories: some with constant heat flux Q and others with constant temperature T, as listed in Table 2.

a) Heat sources with constant heat flux Q: Under certain indoor thermal environment, it is believed that these sources have a constant heat flux Q. These heat sources mainly include solar radiation, lighting, equipment, and occupants. The heat flux depends on the heat produced by these heat sources while it has no relation with the heat transfer process. For example, the heat flux of a male adult in office is 86 W and the heat flux of a computer is about 200 W with a room state of 26 °C and 60% relative humidity [24]. The heat flux of direct sunlight could also be regarded with constant heat flux at a certain moment, although it's variable by time. The value of this heat flux is influenced by outdoor condition, envelope properties and etc. It could be over or less than 100 W/m^2. The surface temperature of the solar radiation is closely related with the indoor environment. For example, the temperature of solar radiation is the floor surface temperature if it's absorbed by the floor.