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A new approach, based on the inverse problem and variation method, for solving building energy and environment problems: Preliminary study and illustrative examples

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ABSTRACT

Building energy systems consume increasing amounts of energy and emit many pollutants (e.g., NO_x, $PM_{2.5}$) and CO_2 into the atmosphere. The problems of air pollution are very serious in China due to the very rapid urbanization and economic development over the past few decades and the fact that most of the primary energy comes from coal in China. In addition, China is facing serious indoor air quality problems caused by various pollutants with both indoor and outdoor origins. These pollutants have been found to be associated with certain diseases. The questions of increasing the energy efficiency of building energy systems and of how to effectively control temperature, humidity and pollutant concentrations in indoor air in an energy efficient way are two great challenges in the field of building energy and environment in China.

Although engineering thermodynamics and heat and mass transfer are fundamental concepts for addressing building energy and environment problems, there are still some limitations in both theories: (1) the former can be used to optimize heat and work conversion processes, but it fails when used to optimize various heat and mass transfer processes and the processes of simultaneous control of indoor temperature, humidity and various pollutants; (2) the latter (including the entransy-based theory) can only be used for analysing or optimizing pure transfer processes.

Based upon the inverse problem and variation method, a new approach is put forward for solving building energy and environment problems. Through illustrative examples we show that this new approach can overcome the limitations outlined above when addressing some building energy and environment problems.

1. Introduction

1.1. Building energy and environmental problems in worldwide

The purpose of building energy systems is to provide a satisfactory built environment. Generally speaking, there are two types of specific building energy systems: passive building energy systems such as building envelopes, and active building energy systems such as heating, ventilation and air-conditioning (HVAC) systems. In addition, the power and heating plants that serve buildings are regarded as extended building energy systems. These building energy systems consume large amounts of energy and emit lots of pollutants (e.g., NO_x, $PM_{2.5}$) and CO_2 into the atmosphere. Over the past two decades, the world's primary energy usage has grown by 49%, with an average annual increase of 2%. Buildings account for 20–40% of the total energy consumption [1,2].

1.2. Building energy and environmental problems in urban China in the past two decades

Over the past two decades, China has experienced rapid urbanization and modernization, which can easily be seen from the indicators in Fig. 1 [3]. During the same period, building energy consumption has increased at a rate of over 10% per year [4]. Buildings consumed 690 million tons of standard coal in China, accounting for 19.1% of the total national energy consumption in 2012 [5]. Along with the dramatically increasing urban areas as well

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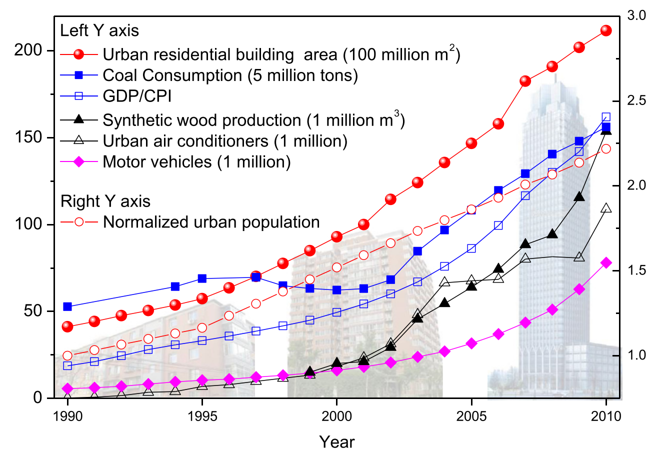

Fig. 1. Various indicators of rapid urbanization and modernization in China during the period 1990–2010. GDP units: *billion RMB*; consumer price index (CPI) in 1990 = 100; urban population normalized by 1990 value (302 million). Revised from Fig. 1 of Ref. [3].

as people's improving standard of living, both the amount and the percentage of building energy consumption are predicted to continue to rise. This raises concerns about energy resource ability, as well as energy system related environmental problems.

The ambient air in many Chinese urban regions has been polluted by emissions from power plants, industrial facilities and motor vehicles over the past two decades. Urban levels of PM_{10}, $PM_{2.5}$, ozone, nitrogen oxides and sulfur dioxide are among the highest in the world [6]. These outdoor pollutants are transported indoors via ventilation and infiltration. Since people spend about 90% of their lifetimes indoors [7], the major exposure to “outdoor pollutants” occurs indoors [8–13].

Although China's IAQ problems caused by pollutants originating both indoors and outdoors started about 20 years later than in developed countries, they have become more serious [14–16].

China has experienced significant increases in certain diseases that have been associated with air pollution. Fig. 2 shows the urban mortality rates in the year 2009 for the top ten fatal diseases in urban China together with the corresponding data in the year 2003

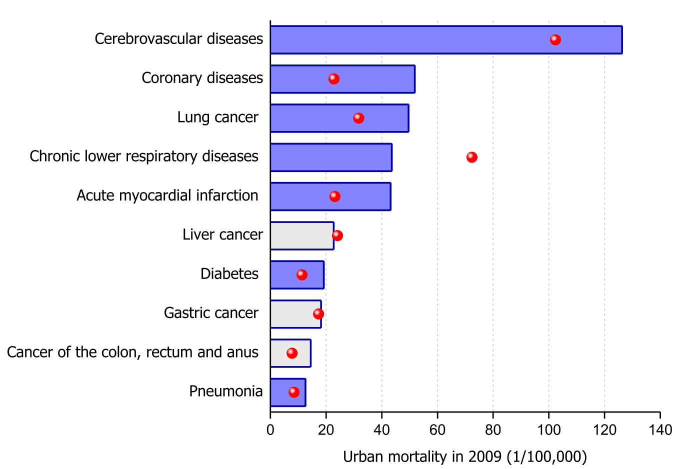

Fig. 2. Top ten diseases responsible for mortality in urban China. The solid blue bars indicate diseases that are caused or exacerbated by air pollution. The red dots indicate urban mortality data for 2003 [3]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[3]. Air pollution is known to, or is suspected of contributing to the origin and severity of seven of these diseases.

1.3. Challenging problems in the field of building energy and environment

How to increase the energy efficiency of building energy systems and how to effectively control the temperature, and humidity of indoor air, and concentrations of airborne pollutants in the indoor environment are important problems in the field of building energy and environment. They are particularly challenging problems in China.

1.4. Limitation of current engineering thermodynamics and heat and mass transfer

Engineering thermodynamics provides a fundamental understanding of building energy systems and indoor environment control systems. However, there are some limitations: (1) engineering thermodynamics can be used to optimize heat and work conversion processes but it fails when used to optimize various heat and mass transfer processes; (2) it focuses on temperature-based processes so that the processes to simultaneously control for indoor temperature, humidity and various pollutants are out of its current scope; (3) it is not applicable to many typical processes involved in controlling the indoor environment.

Heat and mass transfer system or process optimization is important in many applications aimed at the efficient utilization of energy. From a classical thermodynamics view, the irreversibility of any process involving temperature can be characterized by entropy change [17]. Bejan advanced the concept of entropy generation as an indicator for optimizing a heat transfer process [18,19]. Since then, entropy generation has been widely used to evaluate or optimize various heat transfer processes [20]. However, Bejan noted later that the entropy generation minimum was sometimes inconsistent with the greatest efficiency of a counter-flow heat exchanger. This inconsistency is the so-called “entropy generation paradox” [21,22] and it throws into doubt the efficiency of using the minimum entropy generation principle to optimize various heat transfer processes.

Liu et al. pointed out that in principle, entropy is an excellent parameter for analyzing or optimizing a heat-work conversion process, but is not a suitable parameter for analyzing or optimizing a heat transfer process [23]. They concluded that this is the key factor in explaining the “entropy generation paradox”. In order to analyze or optimize a pure heat transfer process, Guo et al. put forward a new concept, entransy, defined as half of the product of the internal energy and the temperature of the object ($G = 1/2mc_pT^2$) [24]. It was found that entransy dissipation occurs during the heat transfer processes due to a “thermal resistance” effect [25]. Since these observations, the extremum principle of entransy dissipation has been found to be very useful in optimizing various heat transfer problems [26–30].

In a system that includes both heat-work conversion and heat transfer subsystems or processes, it is not suitable to optimize its output by using entropy generation or entransy dissipation alone. Optimizing the performance of the whole system is also a challenging problem.

Based upon the inverse problem and variation method, we propose a new approach to solving building energy and associated environmental problems. The main differences between our approach and the traditional engineering thermodynamics approach and Guo et al.'s entransy-based theory [24] are: (1) our approach is not solely applicable to heat-work conversion processes or to heat transfer processes; (2) it is not based on the second