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A review of solar chimney integrated systems for space heating and cooling application

Nima Monghasemi*, Amir Vadiee

Department of Mechanical and Aerospace Engineering, Shiraz University of Technology, Shiraz, Iran

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ABSTRACT

The conventional indoor climate comfort systems have a major share of energy consumption in residential sectors. Passive design is an approach that can reduce building energy demand by minimizing mechanical systems power consumption. Solar chimneys as natural draught components that utilize solar energy to build up stack pressure are an innovative passive design. Solar chimney contributes to an increase in efficiency for residential space heating and cooling in addition to a considerable reduction of greenhouse gas emissions. This article presents an overview of recent progresses in solar chimney research. The construction industry has a tendency in utilization of integrated solar chimney configurations to improve the level of thermal comfort. In this paper, common integrated configurations based on solar chimneys were summarized. Besides, the challenging aspects and recommendations of each system were mentioned. Combined energy systems based on solar chimney have been regarded as efficient strategies toward green building architecture. Each system has its own pros and cons and there is not a general guideline that can arrange these systems in descending order according to their performance. It is necessary to carry out more experiments to solve forthcoming problems in their commercial applications. Further studies are suggested in developing optimization strategies and control systems. A desirable control system responds to inhabitants needs unobtrusively and allows them to change a condition if it is perceived thermally uncomfortable, with prompt feedback.

1. Introduction

Energy use in buildings has a large part of global and regional energy demand. The share of heating and cooling in total building energy demand is very diverse varying between 18% and 73% worldwide [1]. A few decades ago, researchers were concerned about innovative strategies reducing energy consumption in building design. For instance, bioclimatic design involves the application of energy conservation techniques in building construction with the cope of renewable energy sources such as solar energy [2]. One challenging aspect is satisfying the thermal comfort based on bioclimatic design. It can contribute significantly to the climate change and has a considerable overall environmental impact.

Before the invention of modern mechanical systems, all buildings were naturally ventilated. Since energy and environment became two key issues in building design, a large interest in developing ancient architecture took place among the scientists. Solar chimney (SC) is regarded as one of the oldest strategies for passive ventilation. It has been utilized for centuries, particularly in the Middle east by the Persians, as well as in Europe by the Romans [3]. It is a novel design to maximize ventilation effect by inducing a sufficient temperature rise in the chimney with the aim of solar radiation [4].

The operational concept of solar chimneys, Trombe walls and double-skin facades is similar as they are open cavities that induce movement of air with the aid of insolation. Trombe wall is a massive wall mainly used for heating the building. However, with proper modifications cooling can also be achieved. Solar chimneys are mainly used to promote night ventilation, although they can be used to enhance daytime ventilation. They could be mounted on rooftops or attached to the building walls. Vertical chimney is the most common layout. However, it has negative impact on the aesthetic aspect of the building. So it is cheaper and less visual to lay the collector along the roof slope.

The possibility of utilizing a solar chimney is not limited to residential or commercial buildings. Rahman, Chu [5] proposed a natural draft chimney instead of mechanical ventilation for a livestock housing. The reduced ventilation cost led to improved production efficiency and profitability of poultry enterprises. Design aspects and comfort criterions are different for industrial sites and are beyond the scope of the presented paper.

* Corresponding author.
E-mail address: nima8927@yahoo.com (N. Monghasemi).

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The literature survey indicates that a considerable body of literature on SC exists. In recent years there has been a growing interest in introducing innovative strategies taking advantage of solar chimney integrated systems. A few papers have addressed the integrated systems for space heating/cooling. Accordingly, the objective of this manuscript is a contribution to recent progresses in solar chimney application for building ventilation. Moreover, it shows the potential and effectiveness of prospective implementation of integrated systems based on solar chimneys.

Section 2 is devoted to solar chimney independent space heating and cooling applications. The section follows a sequential pattern, describing the analytical and numerical developments of solar chimney and then referring to experimental studies in this field. Section 3.1 is a detailed description of EAHX-SC system; PCM-enhanced solar chimney will be discussed under Section 3.2; water consuming systems based on SCs are covered in Section 3.3; at last, a brief report of PV based solar chimney is outlined under Section 3.4.

2. Solar chimney independent building applications

Due to the general availability of mechanical ventilation devices and improved lifestyle in the 20th century, utilization of wind force or solar energy for ventilation became obsolete. As a result, research and development of solar chimney is fairly limited before 1980s. Over the last few decades, the challenge of reducing greenhouse gas emissions and the need for efficient ventilation aroused the renewed interest in solar chimneys. Many existing research concentrate on model experiments and theoretical investigations to study the geometry, orientation and meteorological parameters on the ventilation performance of solar chimneys [6]. In most solar chimney studies, the main idea was to enhance natural ventilation by considering different design parameters. For instance, the chimney width, stack height, chimney orientation and absorber materials were of practical interest. Khanal and Lei [4] research revealed that most of the studies in the area were based on pure experiments or on an experimental approach coupled with a numerical modeling. Afonso and Oliveira [7] experimental results showed the chimney width was more effective on ventilation rate rather than its height. Mathur and Mathur [8] showed that the optimum absorber inclination angle varies from 40° to 60°, based on the place latitude. While Hamdy and Fikry [9] found out the optimum tilt angle of a solar collector required to provide the best ventilation performance for their experimental model was 60°, this inclination angle was about 45° based on Mathur and Mathur [8] experiments. The optimum tilt angle causes a slight increase in chimney air flow rate for winter applications, so it might not worth the risk of the construction instability. However, the improved ventilation rate for summer months is remarkable and decisions must be made with caution. Ong [10] developed a steady mathematical model of a wall-type solar chimney. The model predicted the thermal performance of the solar chimney as well as the chimney air flow rate. The analytical modeling of velocity and temperature profiles in the chimney showed a good agreement with former experiments for the chimneys with gap-to-height ratio less than 1:10. Because of the fluctuating nature of solar irradiation, it seems difficult to obtain steady state radiation. Martı and Heras-Celemin [11] proposed a dynamic model evaluating the performance of the solar chimney with real weather data acquisition. The theoretical usefulness of the SC in offering nocturnal ventilation in Mediterranean climates was also reported. Lee and Strand [12] examined the effect of chimney height, solar absorptance of the absorber wall, solar transmittance of the glass cover and air gap width under different climate conditions. It turned out that the air gap width had the least impact on the ventilation enhancement among the four input variables. Mathur, Bansal [13] suggested a small size solar chimney with an absorber length less than 1 m. The system installation had priority over the earlier configurations because it could be embedded in a regular window without major structural modifications. Their detailed analysis also revealed that the airflow rate increased with increasing the air gap.

Air change per hour (ACH) is a measure of the air volume added to or removed from a space (normally a room or house) divided by the volume of the space [14]. If the volume of air supply to the inner spaces is sufficient, the temperature would approach the ambient. At an ambient temperature of 20–26 °C, natural ventilation provides thermal comfort for habitation. There is no general guideline finding the optimum ACH for a naturally ventilated house. ACH dependence on many design parameters such as building configuration, number of residents and building function makes it a challenging aspect. Most of the studied literature computed its value without referring to an optimal number [4].

With development of fast numerical schemes, computational fluid dynamic (CFD) methods were quickly growing in solar chimney analysis. CFD usually provides all relevant flow information throughout the domain of interest. In case of a solar chimney, pressure variations and thermal distribution in the chimney are of practical interest. Before the advent of commercial software packages; laminar flow codes were developed to simulate airflow and heat transfer in the solar chimney. The flow conditions in the solar chimney are more in line with turbulent flow regime. Special focus is given to the correct description of turbulence modeling in the literature. $k-$ models are assumed to present more realistic predictions of velocity and temperature profiles as reported by experiments. It is revealed from this review that the $k-$ models provided superior performance for boundary layer flows under adverse pressure gradients. Thus, they have been the main investigation method used in solar chimney research. Fig. 1 illustrates the share of different CFD models adopted in solar chimney study.

A multi-dimensional analysis which is supported in the CFD technique is able to capture prevailing flow phenomena like reverse-flow in contrast with a one-dimensional approach. Reverse flow eventuates as air entrainment occurs at the chimney exit and air penetrates downwards into the chimney. Reverse flow should be avoided through the solar chimney since it results in a reduction of flow rate which is not desirable for ventilation. In order to prevent reverse flow, Khanal and Lei [15] proposed a solar chimney design with an inclined passive wall (glazing) and a vertical active wall (absorber) called inclined passive wall solar chimney (IPWSC). The study verified that there was an optimum chimney height-to-gap ratio suppressing the reverse flow as well as inducing the maximum ventilation rate.

In most theoretical models the assumption of uniform air temperature distribution is considered which might not be valid for large gap-to-height ratios. Another issue is the difficulty arising about the suitable expressions for pressure losses at the inlet, outlet and along the chimney channel. These uncertainties might cause significant deviation

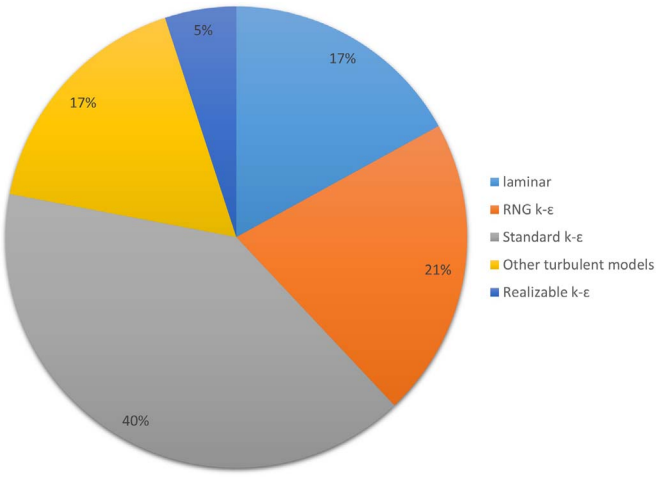

Fig. 1. The share of different CFD techniques used in solar chimney investigations based on the present literature review.