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An optimal design analysis method for heat recovery devices in building applications

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HIGHLIGHTS

- A straightforward optimal analysis method for heat recovery devices in building applications is proposed.
- The proposed method is based on essential characteristics for building applications from the practical point of view.
- The manufacturing and operating cost can be considered synthetically during the optimal design.
- Comparisons are made between different heat exchanger core geometries by employing this method.

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ABSTRACT

Air-to-air heat recovery system is widely used in building applications to reduce the energy used for conditioning the fresh air. The heat exchanger core geometry is one of the key factors that affect the overall performance of a heat recovery system. To better guide the development of high performance heat exchangers in building applications, a new analysis method is proposed in this work from the practical application point of view. The objective of the new optimization method is: at any given mass flow rate, temperature difference and desired heat recovery effectiveness, to minimize the material cost at a specified fan energy use, or alternatively, to minimize the fan energy use at a given material cost. Different duct geometries are analyzed together with the classical j/f factor method: equilateral triangle (Tri), circular (Cyl), square (Squ), rectangle with aspect ratio 1/2 (Rec(1/2)), 1/4 (Rec(1/4)), and 1/8 (Rec(1/8)). A novel channel structure named cross-corrugated triangular (CCT) duct is also considered for comparison. From the energy saving point of view, under the same hydraulic diameter, the pumping power requirements for Rec(1/8) are the lowest when compared with the other shapes in the laminar flow region, while the pumping power requirements for CCT duct are the highest, indicating larger energy consumptions when using such structure. Conversely, with a specified fan power consumption, the required total surface area of Rec(1/8) are the smallest, which means that a parallel plate channel is the best geometry from the material saving point of view. By employing this method, the manufacturing and operating cost can be considered synthetically for achieving an optimal design. The proposed method can be used to select target-oriented high performance heat recovery core geometry for desired heat recovery performance, resulting in reduced space, weight, support structure, energy requirement and lifetime cost.

1. Introduction

With rapid economic growth, there is a growing desire for better indoor built environment. Both thermal comfort and indoor air quality issues have gained increasing attention. Adequate ventilation is necessary to maintain a desired indoor air quality [1,2]. As a result, the energy consumption in buildings is increased due to the expansion of building sectors and the growth of ventilation system [3–5]. Energy saving technologies have attracted increasing attention due to global warming and environmental impact issue [6–9]. Air-to-air heat recovery systems employed in buildings could save a large fraction of the energy that is used for conditioning the fresh air, and theoretically reduce the energy consumption by a few significant percentage points [10]. Thus it comes into widespread use and has currently become a requirement in building designs [11].

Heat recovery systems include sensible heat recovery and enthalpy (sensible and latent) heat recovery. Different types of heat recovery systems, such as heat pipe [12,13], rotary wheel

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[14], run-around coil [15], and fixed plate [16], have been utilized to recover energy between the supply and exhaust airflow. A comprehensive review about the heat recovery technologies used in building applications has been made by Mardiana-Idayu and Riffat [17]. The efficiency and advantages of these technologies were summarized in that study. It is found that the works in the past had emphasized more on heat or mass transfer augmentation in heat exchanger. When the building standards are introduced, the performance of heat recovery becomes a concern [18–20].

The overall performance of a heat recovery system is affected by many factors that include the material property, operating condition, and heat exchanger core geometry. Various technologies have been developed to increase sensible and latent effectiveness of a stationary heat recovery heat exchanger, including material side intensification and air side intensification. From material side, membrane based heat recovery ventilators have attracted much attention due to its superior moisture-recovery effectiveness. Encouraging results are emerging with the introduction of new materials that can offer moisture recovery at the same time [21], and nano materials breakthroughs are offering new opportunities [22]. From air side, the use of compact heat exchangers is an effective method to intensify heat mass transfer [23,24]. Related investigations have been conducted to reveal the effect of different surface geometries on the performance of heat recovery heat exchangers. In practice, many other factors affect the end performance of a heat exchanger, such as limited heat exchanger size, reduced temperature difference, and reduced fan power [25].

The basic performance data for a heat exchanger are often shown as j (Colburn factor) or Nu (Nusselt Number) and f (Fanning friction factor) vs. Re (Reynolds number) curves. Since Kays and London presented j and f vs. Re for a large number of compact surfaces in 1984 [26], this kind of plot curves have become a customary tool for presenting performance data for heat transfer surface geometries [27–34]. Yet, such evaluation method will only give a partial indication of performance. It is a common knowledge that heat transfer enhancement can be obtained but with a larger pressure drop penalty. Sometimes, the benefits gained from heat transfer enhancement are not great enough to offset the increased friction losses. Sparrow and Comb [35] evaluated the effect of channel height on the flow and heat transfer characteristics on a corrugated-wall heat exchanger. It was found that the increase of the channel height resulted in a substantial increase in the Nusselt number but the friction factor increased to a greater extent. This kind of enhancement may be acceptable when the designer's objective is focused on increase of heat transfer, but is not desired in heat recovery applications. Heat recovery systems used in building applications recover thermal energy, but use electrical energy for the fans, which may be more precious than the saved heat [36,37]. Other performance parameters were developed due to the failure of j and f curves to portray the relative performance. The ratio of the Colburn factor to friction factor (j/f) establishes a relation between friction and heat transfer coefficient, and is widely used for many comparative studies [28,30,38–41]. This factor is a useful parameter when comparing surfaces with different cross-sectional shapes. However, the influence of the scale of the geometry is not taken into consideration when using this parameter. Also, the performance evaluation is made through the comparisons of the corresponding j/f values under the same Reynolds numbers, which means the air flow rate may not remain constant for different surface geometries. Thus the significant effect introduced by the airflow rate is overlooked by using this parameter. The performance analysis on heat recovery heat exchangers should be conducted based on the same environmental and operating conditions. From an energy saving point of view, which is the primary purpose for using heat recovery system in building applications, the pressure drop, i.e. electricity consumption for fans, should be seriously considered. On the other hand, the designer may not always choose the best heat exchanger with minimal energy use, since he must consider the space available, and the required total surface area which is related to the material costs.

Generally there are two categories of methods for performance analysis on heat exchangers. One is the performance evaluation criteria (PEC) based on the first law of thermodynamics, which define the performance benefits of an exchanger having enhanced surfaces, relative to a standard exchanger with smooth surfaces subject to various design constraints [42–44]. Twelve criteria include three different types of constraints on the geometry of the heat exchanger are developed: fixed geometry (FG), fixed flow area (FN), and variable geometry (VG) criteria. However, these criteria are segregated by corresponding constraints, which result in that the criteria cannot be widely used in comparative studies. For example, one of the FG criteria seek reduced fan power for

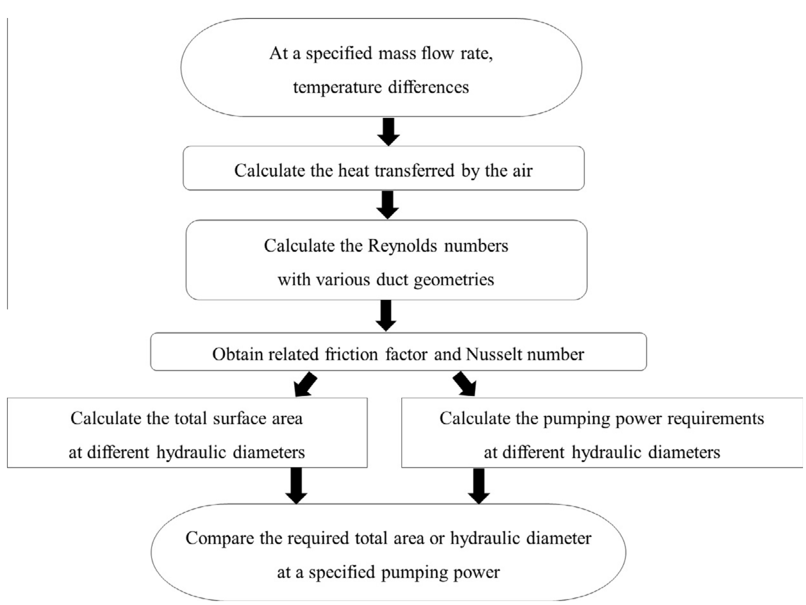

Fig. 1. The presented analysis process for the optimal design.