Energy and Buildings 110 (2016) 453–467

Contents lists available at ScienceDirect

Energy and Buildings

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

The application of linear regression and the power law relationship of air-side heat transfer with field measurements to model the performance of run-around heat recovery systems

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ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form
29 September 2015
Accepted 12 October 2015
Available online 21 October 2015

Keywords:
Run-around heat recovery system
Supply air temperature efficiency
Power law relationship of air-side heat transfer
Linear regression
Heat recovery efficiency

ABSTRACT

Improving the performance of air-to-air heat recovery systems, as measured by supply air temperature efficiency, is an important energy saving strategy that is often regulated by building codes. The high nonlinearity of supply air temperature efficiency with airflow rate in a run-around heat recovery system makes the trend prediction of supply air temperature efficiency especially challenging for field measurement. This paper proposes a simple and novel field measurement based methodology, supported by the power law relationship of air-side heat transfer, to evaluate the performance of run-around heat recovery systems. A system dependent power, *signature power*, is proposed that establishes a linear relationship between the supply air temperature increment across the supply air heat exchanger and a parameter—the maximum temperature difference between exhaust and supply airstreams divided by the signature power of the supply airflow rate. This methodology can predict the supply air temperature efficiency and is verified using four run-around heat recovery systems with field measurements. This new methodology can possibly be applied to other types of air-to-air heat recovery systems. This paper also describes a tuning method for determining the signature power based on field measurements and addresses the heat recovery efficiency of run-around heat recovery systems.

1. Introduction

100% outdoor air ventilation systems are commonly used in commercial and residential buildings in Finland as well as in other European countries [1]. This type of system introduces 100% outdoor air, heats and cools it, may humidify or dehumidify it, and then supplies this treated air to the conditioned space [2]. The main advantage of a 100% outdoor air system is that it can easily control the amount of outdoor air brought into the space to meet the minimum requirements for outdoor air in order to ensure good indoor air quality (IAQ) in accordance with industry standards, such as ASHRAE Standard 62.1 [3]. An air-to-air heat and/or moisture recovery process is often included in outdoor air delivery systems to recover heat and/or moisture from the exhaust air by employing heat exchangers. This process can sometimes save up to 80–90% of the heating energy requirements for the supply air [2]. Because of the potential for energy savings, air-to-air heat recovery systems are now often required in building design. For example, in Finland, an air-to-air heat recovery system is required to recover at least 30% of the heating energy needed for heating the outside air with energy recovered from the exhaust air of the ventilation system [4]. There are several types of air-to-air heat recovery systems. The run-around (coil) heat recovery systems are a type often used in Finland. This system uses two physically separated heat exchangers (coils) in the air supply and exhaust ducts to recover and transfer heat between them by using an intermediate heat transfer liquid such as an ethylene glycol antifreeze solution. Because a run-around system does not require the supply and exhaust air ducts to be located side by side, this gives them an advantage over other types of systems. This is important when cross contamination is a concern or in retrofit applications where the exhaust and supply air ducts have already been installed far apart [5]. The main disadvantage of this system is that using an intermediate liquid as a heat transfer medium will reduce the system's efficiency and electricity is required for pumping liquid. However, the energy required for pumping the liquid is significantly less energy-intensive than moving air with fans [6].

Because system retrofitting is relatively easy, the application of run-around systems has become a priority topic for research and modeling them for studying air-to-air heat recovery system is

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http://dx.doi.org/10.1016/j.enbuild.2015.10.028
0378-7788/

Nomenclature

A	area (m^2)
ANN	artificial neural network
CAV	constant air volume
C_p	specific heat (kJ/kg °C)
h	heat convective coefficient (W/m^2 °C)
m	mass flow rate (kg/s)
m	power for air heat convective coefficient
MAE	the mean of absolute errors
MAPE	the mean of absolute percentage errors
MSE	the mean of the sum of square errors
NTU	the number of transfer units
Nu	Nusselt number
Pr	Prandtl number
R^2	coefficient of determination
Re	Reynolds number
t	temperature (°C)
U	overall heat transfer coefficient (W/m^2 °C)
$\dot{V}$	airflow rate (m^3/s)

Subscripts

ea	exhaust air after passing through the exhaust air heat exchanger
eb	exhaust air before passing through the exhaust air heat exchanger
ex	exhaust air
increment	temperature increment across the supply air heat exchanger
max	maximum temperature difference between exhaust and supply airstreams
max	maximum
min	minimum
o	outdoor air
s	surface
sa	supply air after passing through the supply air heat exchanger
sb	supply air before passing through the supply air heat exchanger
sh	heat recovery efficiency for the supply air
sup	supply air

Greek letters

α,β	signature power
ε	disturbance, noise or error
η	system efficiency
ρ	density (kg/m^3)

also considered important. Relevant research is typically performed using a numerical model to predict the performance of the system with different configurations of heat exchangers, liquid heat transfer fluids, liquid flow rates, pumps and outdoor conditions [5,7–11]. Vali et al. [5] presented a numerical model of a run-around heat recovery system with two identical counter/cross flow plate heat exchangers. They found the overall effectiveness of the heat recovery system with two identical counter/cross flow heat exchangers is a function of the number of transfer units (NTU), the heat capacity rate ratio of the fluids (Cr), the aspect ratio of the exchangers, and the entrance ratio of the exchangers. The model was verified using correlations from the published literature for heat exchangers and run-around heat recovery systems employing air–liquid cross flow and counter-flow arrangements. Fan et al. [7] developed a two-dimensional steady-state mathematical model to study the heat and water vapor transport in a run-around heat and moisture exchanger coupled with a lithium bromide solution for air-to-air exchanger applications. The overall effectiveness of the run-around energy recovery system was shown to be dependent on the flow rate of both the pumped fluid and airflow, the size and design of each exchanger, and the inlet operating conditions. Hemingson et al. [8] presented the steady-state performance of a run-around membrane energy exchanger (RAMEE) for a wide range of outdoor air conditions using a numerical model. The effectiveness values were shown to be very dependent on outdoor conditions which results in some effectiveness values exceeding 100% or being less than 0% for several of the outdoor air conditions investigated. The heat and moisture transfer was shown to influence the latent and sensible performances of the RAMEE, respectively. Other numerical models are included in references [9–11].

Although a numerical model is effective for studying the performance behavior of a run-around system for different system configurations, it is computationally intensive [12]. On the other hand, artificial neural networks (ANNs) are gaining popularity because they are easy to implement and use and can model high levels of non-linearity and highly complex and ill-defined problems with incomplete information [13]. Applications of ANN to modeling heat exchangers, including the run-around heat recovery system, have been widely reported. Akbari et al. [12,14] developed ANN models to predict the steady state and transient heat and moisture transfer performance (i.e., the sensible and latent effectivenesses) of a run-around membrane energy exchanger (RAMEE). The training data set was produced using an experimentally validated finite difference (FD) model and a transient numerical model (TNM). Diaz et al. [15] trained an ANN to estimate the heat transfer rate for a single-row plate-fin heat exchanger. Training data for this model were obtained in the laboratory. Pacheco-Vega et al. [16] applied the ANN approach to model the thermal characteristics of heat exchangers used in refrigeration systems. The training data were experimental data from a series of tests of several multi-row, multi-column, fin-plate type heat exchangers with staggered tubes provided by a manufacturer. Peng et al. [17] used ANN to predict the pressure drop and heat transfer characteristics in plate-fin heat exchangers (PFHEs). In this case, the ANN was trained using limited experimental data from a series of tests of several fin geometries consisted of a wind tunnel subsystem, a steam-condensation water loop and the measuring subsystem. Xie et al. [18] applied ANN for the heat transfer analysis of shell-and-tube heat exchangers with segmental baffles or continuous helical baffles. Limited experimental data were obtained from the laboratory for training and testing the neural network configurations.

Despite the significant level of effort thus far, field measurement based studies for run-around heat recovery systems are relatively rare in the literature. Field measurement has a major advantage over numerical models and laboratory work—it can show the actual behavior of a run-around heat recovery system. But there are several theoretical and practical issues that make field measurement studies quite difficult:

- Most ventilation systems are constant air volume (CAV). In Finland the majority of ventilation systems provide just two ventilation rates: one for daytime and another for nighttime. It is important to know how the performance of a run-around heat recovery system is affected by changes in the airflow rate. For a CAV system, black-box models such as ANN cannot determine the performance of a run-around heat recovery system as a function of airflow.
- Additionally, a CO_2-based demand-controlled ventilation (DCV) system cannot ensure sufficient information for ANN to determine the true relationship between airflow rate and system performance because (1) the air-side heat transfer of a run-around system is extremely complex; (2) a wide range of