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Determination of air-to-air heat wheel sensible effectiveness using temperature step change data

F. Fathieh [a,*], R.W. Besant [a], R.W. Evitts [b], C.J. Simonson [a]

[a] Department of Mechanical Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada
[b] Department of Chemical & Biological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada

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ABSTRACT

The determination of the effectiveness of large heat wheels using standard measured data and test conditions can be very expensive and time consuming. The main contribution of this paper is that it tests heat wheel components rather than the wheel itself. In addition, this paper deals directly with the question of what accuracy can be achieved for the determination of sensible energy effectiveness by using a transient step change method for the exchanger matrix materials in a test cell. In this study, the sensible effectiveness of heat wheels is predicted by performing a number of cyclic and single step change transient experiments on a parallel-plate heat exchanger. A new experimental facility is developed to cause a step change for the inlet air temperature of the exchanger. In the cyclic tests, the heat exchanger is exposed to a periodic inlet temperature steps; afterward, the sensible effectiveness of parallel-flow and counter-flow heat wheel, comprised of the same material as parallel-plate exchanger, is determined using the obtained temperature profiles. It is find that this method can be used to determine the sensible effectiveness of parallel-flow heat wheel. However, the high uncertainty found in the sensible effectiveness of counter-flow heat wheel, ±32%, makes the results unreliable. In the single step-change test, a time constant is assigned to the exchanger response when it is subjected to a step change in inlet temperature. The time constant is obtained by fitting the experimental data to a first order exponential time response curve. An analytical solution posits that the effectiveness of the heat wheel depends only on the product of the time constant and the wheel angular speed, or angle ratio. Comparing values of the sensible effectiveness calculated through available empirical correlations and the ones obtained by single step change experiment showed less than 3% difference in results when the heat capacity rate ratio is greater than 5. It is concluded that due to simplicity, accuracy, and low cost of the single step change experiments, it is the preferred method to determine the effectiveness of heat wheels operating at a specified rotary speeds, provided the flow channel geometries and Reynolds numbers for both the wheel and the small-scale test cell.

1. Introduction

Despite the limited amount of energy resources, world energy consumption has been increasing in a few last decades. In developed countries, about 40% of the total energy is consumed in commercial and industrial buildings, where more than 50% of this amount goes for heating, ventilation, and air-conditioning (HVAC) of buildings [1]. Thus, many governmental agencies put regulations on energy consumed by HAVC systems and equipment [2]. On the other hand, due to the amount of time that people spend indoor, occupant thermal comfort and indoor air quality (IAQ) of buildings are directly related to individual's health and productivity[3]. Based on regulations, IAQ must be adjusted to a certain condition according to energy conservation as well as health consideration [4]. In addition, air pollution, climate change, and ozone depletion are known as an adverse side effects of energy consumption of HVAC systems and refrigerants [5].

Recently, more efficient HVAC systems being designed with air-to-air energy recovery systems that recuperate a large portion of the energy needed to condition ventilation air for commercial and industrial buildings. Heat (sensible) wheels are one of the most effective energy recovery systems. Over the past 25 years, due to their relatively high effectiveness and low manufacturing costs, heat wheels have been widely used in HVAC systems and cabinet units. Fig. 1 shows a schematic of a heat wheel with the supply

* Corresponding author. Tel.: +1 (306) 203 3232.
E-mail address: Farhad.Fathieh@usask.ca (F. Fathieh).

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Nomenclature

A_{duct}	cross-sectional area of the each duct (m^2)
A_{ht}	total heat surface area of the exchanger (m^2)
b_{ch}	width of exchanger channels (m)
C_p	specific heat capacity [J (kg^{-1} K^{-1})]
C_r^*	heat capacity rate ratio
d_h	hydrodynamic diameter of channels (m)
f	input forcing function
h	convective heat transfer coefficient [W (m^2 K^{-1})]
h_{ch}	height of exchanger channels (m)
L_{ch}	length of exchanger channels (m)
M	mass of matrix (kg)
$\dot{m}_a$	air mass flow rate (kg K^{-1})
Ntu	number of transfer unit on the supply or exhaust side
Q_f	volumetric air flow rate (L s^{-1})
Re	Reynolds number
t	time (s)
t_s	student t-factor
U_B	bias (systematic) uncertainty
U_P	precision uncertainty
U_T	total uncertainty
V_f	air flow face velocity (m s^{-1})
$x_{h,FD}$	hydrodynamic entry length (m)
$xt_{h,FD}$	thermal entry length (m)

Greek symbols

Δ	difference between the exchanger outlet and inlet conditions
δm	thickness of the exchanger sheets (m)
θ	normalized temperature
ρ	density (kg K^{-1})
τ	time constant of exchanger response (s)
ψ	angle ratio
ω	wheel angular speed [s^{-1}or rpm]

Subscript

a	airflow
c	cold airstream
ε	sensible effectiveness
ch	channels
CF	counter-flow
FD	fully-developed
h	hot airstream
i	exchanger inlet
m	matrix
o	exchanger outlet
PF	parallel-flow
st	step change

and exhaust airstreams. As wheel rotates with specified angular speed, heat is continuously transferred between supply and exhaust airstreams with different temperature. Heat transfers from the hot airstream to the wheel matrix as the hot airstream, supply air in summer or exhaust air in winter, passes through the wheel made up of a large number of flow channels. The stored heat in the wheel is transferred to the cold airstream as the wheel rotates 180°. This phenomenon repeats as wheel rotates continuously. Most recently, heat wheels have been updated to a heat and moisture exchanger so-called energy wheels. Energy wheels operates under the same principle as heat wheels with the flow channels coated by micron size desiccant particles such as silica gel or molecular sieve. Energy wheels are capable of recovering both sensible and latent energy, mostly used in the USA, Asia, and Canada, while heat wheels only recover sensible energy and are still extensively used in Europe [6]. Moreover, in recent application of heat wheels, they are combined with other types of energy exchangers (energy wheels, flat plate membrane, liquid-to-air membrane) to enhance the coefficient of performance (COP) of the system and prevent frost formation in energy exchangers [7]. In fact, heat wheels are still of great interest of HVAC designers and widely used in recent HVAC units.

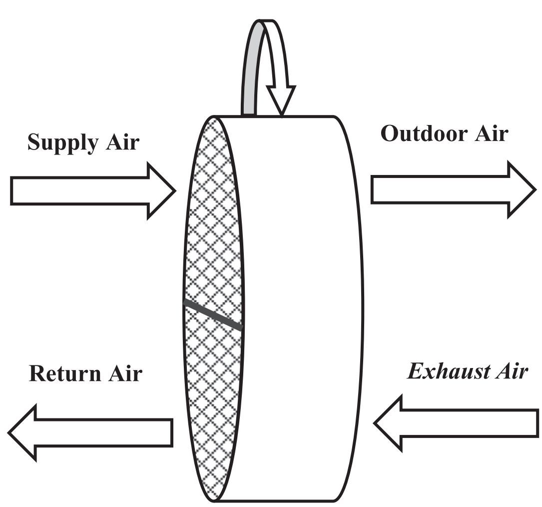

Fig. 1. Schematic of heat recovery wheel with supply and exhaust airstreams.

ANSI/ASHRAE ARI standard 1060-2011 [8] and standard 84-2013 [9] provide method for testing air-to-air heat exchangers with an acceptable range of uncertainties. Sensible effectiveness is defined as the ratio of the heat transferred between hot and cold airstreams to the maximum possible amount of heat which can hypothetically recovered by the wheel, through steady-state operating conditions. Finding sensible effectiveness with acceptable uncertainty limits requires extensive testing facilities, expensive instrumentation, time consuming tests, and a large number of data with online analysis [10,11].

Many studies have been done to investigate the sensible effectiveness of heat recovery wheels both theoretically and numerically. Some researchers attempted to solve the partial differential governing equation applied within the wheels flow channels under simplifying assumption [12,13]. However, due to complexity and inaccuracy in the results, the solutions were not appreciated by wheel designers and manufacturers. Instead, most of the reliable data is in the form of correlations proposed by Kays and London [14]. They derived a correlation based on the results of a comprehensive study on heat regenerative wheels done by Lamberston [15] and Bahnke and Howard [16]. For the same supply and exhaust air heat capacity rate, their correlation can be simplified as follow:

$$\varepsilon = \left(\frac{Ntu}{1 + Ntu}\right)\left(1 - \frac{1}{9C_r^{*1.93}}\right) \quad (1)$$

where dimensionless $Ntu = hA_{ht}/\dot{m}_a C_{p,a}$ is number of transfer unit in which h is convective heat transfer coefficient, A_{ht} is heat transfer surface area, $\dot{m}_a$ and $C_{p,a}$ are the mass flow rate and specific heat