Energy and Buildings 84 (2014) 316–323

Contents lists available at ScienceDirect

Energy and Buildings

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

Experimental analysis and practical effectiveness correlations of enthalpy wheels

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ARTICLE INFO

Article history:
Received 4 April 2014
Received in revised form 30 July 2014
Accepted 1 August 2014
Available online 11 August 2014

Keywords:
Enthalpy wheels
Energy efficiency
Experimental test
Correlation
Effectiveness
Pressure drop

ABSTRACT

Air to air heat exchangers play a crucial role in mechanical ventilation equipment, due to potential primary energy savings in new buildings or in case of refurbishment of existing ones. In particular, interest in enthalpy wheels is increasing due to their low pressure drop and high effectiveness. In this work two different enthalpy wheels, a silica gel and a calcium carbonate based wheel, respectively, are tested. Sensible and latent effectiveness are evaluated in many working conditions, in particular with balanced and unbalanced air flows and with different inlet air temperature, humidity and wheel revolution speed. For each wheel, at nominal revolution speed, practical correlations of sensible and latent effectiveness and of pressure drop are proposed. The obtained correlations predict appropriately actual enthalpy wheels performance. Therefore they can be easily used in energy simulation programs to predict effectiveness and pressure drop of enthalpy wheels used for heat and water vapour recovery in buildings.

1. Introduction

It is well known that buildings are responsible for around 40% of primary energy consumption in developed countries and for 20–40% in developing countries [1]. In the construction of new buildings or in case of refurbishment of existing ones, the use of heat exchangers between exhaust and fresh air streams can provide relevant energy savings, reducing both heating and cooling load [2,3]. In particular, interest in enthalpy wheels is increasing due to sensible and latent heat recovery capability, low pressure drops and high effectiveness.

An enthalpy wheel consists of a cylindrical rotating device made of rolled-up corrugated sheets of metallic material (such as aluminium), in order to get a great number of parallel channels with a typical sinusoidal or triangular cross sectional geometry (Fig. 1). The metallic substrate is coated with a sorption material, such as silica gel, activated alumina, molecular sieve or calcium carbonate, which is able to adsorb water vapour. Two air streams pass through the cross section area of the device: typically the outside fresh air stream, referred to as supply air, and the exhaust one, which is the return air flow from the building. A purge sector between exhaust and process air streams can be used to reduce contamination of the fresh air flow.

Heat and moisture are transferred from the former air stream to the wheel matrix and then from the matrix to the latter air stream. For a given enthalpy wheel, operating parameters such as revolution speed, supply and exhaust air temperature, humidity and velocity, influence the behaviour of the component.

When energy analysis of buildings and HVAC systems is carried out, enthalpy wheel performance should be properly evaluated. A simplified approach is often used in literature: sensible and latent effectiveness are assumed constant or are determined by linear interpolation of values at different air flows [4,5]. In spite of its simplicity, it may lead to improper performance evaluation because these terms are not constant over a wide range of working conditions. For this reason several works are available in literature in order to properly predict the behaviour of enthalpy wheels.

Many detailed models have been developed, solving heat and mass transfer equations [6–10]. This approach is particularly suitable to design enthalpy wheels and analyse its performance, but it requires high calculation time because a system of partial differential equations should be solved. Although studies to simplify the set of governing equations have been already proposed [11–14], correlation based approach would be certainly more suitable for energy simulation tools since it is faster and more effective than the previous one.

Rabah et al. [15] tested a commercial sensible heat wheel, with supply air temperature ranging from 40 °C to 70 °C, providing effectiveness correlations based on Kays and London [16] equations. These working conditions are interesting for desiccant evaporative

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http://dx.doi.org/10.1016/j.enbuild.2014.08.001
0378-7788/

Nomenclature

a_c	channel height [mm]
A	area [m^2]
$A, B\ldots N$	test set
b_c	channel base [mm]
D	diameter [m]
cp	moist air specific heat [J kg^{-1} K^{-1}]
$C_{1,2\ldots10}$	correlation parameters
$D_{1,2}$	duct
$EW1$	enthalpy wheel no. 1
$EW2$	enthalpy wheel no. 2
L	enthalpy wheel length [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
$n_{1,2,3}$	correlation exponents [−]
N	revolution speed [rev min^{-1}]
NTU	number of transfer units [−]
p	pressure [Pa]
$\dot{Q}$	heat transfer rate [W]
R	ratio between the minimum and maximum inlet air velocity times air density [−]
T	temperature [°C]
UA	overall heat transfer conductance times surface area [W K^{-1}]
u_ε	effectiveness uncertainty [−]
u_{xi}	uncertainty of a generic measured parameter [°C, Pa or %]
$u_{xi,inst}$	instrument uncertainty of a generic measured parameter [°C, Pa or %]
v	face velocity [m s^{-1}]
x_i	generic measured parameter [°C, Pa or %]
X	humidity ratio [kg$_v$ kg$_{da}$$^{-1}$]

Greek symbols

α, β	effectiveness correction terms [−]
φ	relative humidity [%]
Δp	pressure drop [Pa]
ε	effectiveness [−]
λ	water latent heat of vaporization [J kg^{-1}]
ρ	density [kg m^{-3}]
ν	cinematic viscosity [m^2 s^{-1}]

Subscripts

a	air
ave	average
d	distributed pressure drop
EW	enthalpy wheel
ea	exhaust air
h	hub
in	inlet
l	local pressure drop
L	latent
o	outer
op	orifice plate
out	outlet
S	sensible
sa	supply air
tot	total
$vsat$	saturated water vapour

cooling cycles but they do not represent typical inlet air conditions of heat exchangers for energy recovery in buildings.

Several authors [17–19] provided simplified effectiveness correlations of enthalpy wheels, obtained from numerical results of detailed component models, instead of directly from experimental data. Stiesch [17] proposed sensible and total effectiveness correlations as a function of temperature, number of transfer units, and dimensionless revolution speed, considering balanced flows and constant exhaust air temperature. Simonson and Besant [18] developed complex correlations of sensible and latent effectiveness, in particular they considered the effect of the adsorption isotherm, the ratio of latent to sensible heat exchanged, the average temperature and the average relative humidity. Finally Jeong and Mumma [19] developed effectiveness correlations as a function of inlet air temperature, relative humidity, and face velocity, providing two equations that require several coefficients.

All in all there is a lack of correlations that can be easily adopted in yearly basis energy simulation tools, in order to predict sensible and latent effectiveness and pressure drop of enthalpy wheels. In this work two different enthalpy wheels, that represent the state of the art in the field, are experimentally tested and practical equations to predict their performance are proposed.

2. Experimental methodology

2.1. Experimental setup

The facility is designed to provide two air streams at accurate controlled conditions of temperature, humidity and flow. The two air streams, denoted as the supply air and the exhaust air, feed the enthalpy wheel in a counter current arrangement. A schematic representation of the experimental setup is shown in Fig. 2.

Temperature and humidity are properly controlled through heating coils, cooling coils and evaporative coolers, in order to reach most typical working conditions of enthalpy wheels in HVAC systems. The supply air stream unit is equipped with additional electrical heaters to adjust flow temperature up to 120 °C (in recirculation mode) for desiccant wheels tests. The enthalpy wheel casing is divided in four equal partitions in each side. Each stream enters and leaves the wheel through two partitions connected with two parallel flexible ducts. Temperature and relative humidity of each air stream are measured at the inlet (in one point) and outlet (in two points) of the wheel through sensors located in the cross section of the duct. As reported in Fig. 2 and in Table 1, temperature is measured by RTD PT100 sensors, relative humidity by capacitive sensors and pressure by piezoelectric transmitters.

Volumetric flow rates are set by variable speed fans and are measured across an orifice plate. Each air stream flows in two different parallel ducts and pressure drop is measured across the orifice plate. Each duct can be excluded in case of low volumetric air flow tests to limit measurement uncertainty. Orifice plates and ducts apparatus are constructed according to DIN EN ISO 5167-2 standards [20]. Maximum supply air flow rate is 2000 m^3 h^{-1} while maximum exhaust air flow rate is 1400 m^3 h^{-1}. Maximum volume flow rates achievable on the two air handling units are different since the experimental facility has been designed to test not only enthalpy but also desiccant wheels: in this case air flow across the wheel can be set unbalanced, which is quite a common condition especially at high regeneration temperatures.

Table 1
Sensors main data.

Abbreviation	Type of sensor	Accuracy*
$T1$**	PT 100 Class A	±0.2 °C
$T2$	PT 100 Class A	±0.2 °C
RH**	Capacitive	±1% (between 0 and 90%)
P	Piezoelectric	±0.5% of reading ±1 Pa

* At T = 20 °C.
** Temperature and relative humidity probe.