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Energy and cost savings potential of oscillating heat pipes for waste heat recovery ventilation

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ABSTRACT

The feasibility of using finned oscillating heat pipes (OHPs) for heat exchange between counter-flowing air streams in HVAC air systems (i.e., outdoor and exhaust air flows), along with the associated cost savings in typical North American climates, is investigated. For a prescribed temperature difference and volumetric flow rate of air, rudimentary design parameters for a viable OHP Heat Recovery Ventilator (OHP-HRV) were determined using the ε-NTU (effectiveness-Number of Transfer Unit) method. The two-phase heat transfer within the OHP-HRV is modeled via effective evaporation/condensation heat transfer coefficients, while the latent heat transfer required to initiate OHP operation via boiling and evaporation is also considered. Results suggest that an OHP-HRV can possess a reasonable pressure drop ($<$200 Pa) and is capable of achieving heat recovery rate $>$5 kW. The proposed OHP-HRV can possess an effectiveness near 0.5 and can pre-cool/heat HVAC air by $>$ 5°C. Potential energy and cost savings associated with using an OHP-HRV were estimated for commercial building envelopes in various regions of the United States. It is found that the proposed OHP-HRV can save more than \$2500 annually in cities that have continental climatic conditions, such as Chicago and Denver, and for the selected locations the average yearly cost savings per building is found to be on-the-order of \$700. Overall, the OHP-HRV shows potential in effectively reducing energy consumption and the operational cost of air handling units in buildings.

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1. Introduction

Engineering new renewable/alternate energy harvesting systems is a global priority. Discovering methods to enhance their performance while reducing their installation costs can lead to the overall reduction of end-user energy costs and greenhouse emissions. One method for accomplishing waste heat recovery in many heating, ventilation and air conditioning (HVAC) systems is to transfer heat between adjacent, enclosed air streams at different temperatures. In this way, an otherwise 'wasted' temperature potential between incoming and exhaust air streams can be beneficially utilized; as long as any air stream intrusion possesses a reasonable pressure drop. Roth et al. (2002) highlighted that air-to-air heat exchangers for the building heat recovery ventilation applications can provide a significant energy savings potential, however these devices are still not being widely adopted in US infrastructure.

Heat recovery ventilators (HRVs) are air-to-air heat exchangers that perform sensible waste heat recovery in residential, commercial, and industrial applications (Roth, 2012). They pre-condition building supply air by utilizing otherwise wasted temperature gradients between air supply and exhaust. These types of heat exchangers can be, for example, enthalpy wheels, fixed plate heat exchangers (FP-HEs), heat pipe heat exchangers (HP-HEs), and oscillating heat pipe heat recovery ventilators (OHP-HRVs). Enthalpy wheels are typically configured to rotate slowly between adjacent air streams; absorbing heat and moisture from the exhaust air and delivering it to the supply air. For equal mass flow rates in counter-flow, enthalpy wheels can achieve a sensible effectiveness on-the-order of ~80% (Shang and Besant, 2008). Pressure drops of 200–500 Pa are representative for typical flow velocities across enthalpy wheels (Casalegno et al., 2011; Markusson et al., 2010). FP-HEs are generally made of aluminum and consist of a series of plates placed equidistant to each other joined by welding, gluing, or folding. For an airflow rate of 300 CFM, FP-HEs can have a typical effectiveness of 70%–80% with pressure drops between 225–275 Pa (Roth, 2012). FP-HEs require less maintenance than enthalpy wheels as they possess no moving parts, but can require more up-front costs (Roth, 2012).

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Nomenclature

A	Area (m^2)
A_{total}	Total heat transfer area of OHP-HRV (m^2)
A_{min}	Minimum free flow area of OHP-HRV (m^2)
A_p	Primary area of OHP (un-finned area) (m^2)
c_p	Specific heat capacity (J/kg K)
C	Total heat capacity (W/K)
C_r	Heat capacity ratio
D	Diameter (m)
D_c	Tube diameter including fin collar (m)
E_{fan}	Fan energy consumption (W)
f	Friction factor
F_p	Fin pitch (m)
G	Mass flux rate (kg/s m^2)
h	Heat transfer coefficient (kW/m^2 K)
h_{fg}	Latent heat of vaporization (J/kg)
j	Colburn j-factor
k	Thermal conductivity (W/m K)
L_1	Height of OHP-HRV (m)
L_2	Depth of OHP-HRV (m)
L_3	Width of OHP-HRV (m)
m	Fin heat transfer parameter (m^{-1})
$\dot{m}$	Mass flow rate (kg/s)
N	Number of fins
N_f	Number of fins per inch (height-wise)
N_r	Number of rows in OHP-HRV (number of OHPs)
N_t	Number of OHP-HRV tubes
NTU	Number of transfer units
Pr	Prandtl number
Q	Heat transfer rate (W)
$Q_{delivered}$	Hourly heating/cooling load (kW)
Q_{rcv}	Hourly waste heat recovery rate (kW)
R''	Thermal resistance (m^2 K/W)
r_n	Bubble radius (m)
Re	Reynolds number
S	Tube pitch (m)
T	Temperature (°C)
T_v	Vapor bubble temperature (°C)
T_{OAT}	Hourly averaged outdoor air temperature (°C)
T_{SAT}	Supply air temperature (°C)
t	Thickness (mm)
t_w	Tube wall thickness (mm)
U	Overall heat transfer coefficient (W/m^2 K)
V	Air velocity (m/s)
v	Specific volume, m^3/kg
$\dot{V}$	Volumetric air flow rate (m^3/s)
ΔE_{comp}	Hourly energy reduction while cooling (kW)
$\Delta E_{cooling}$	Hourly energy savings while cooling (kW)
$\Delta E_{furnace}$	Hourly energy reduction while heating (kW)
ΔE_{fan}	Increase in hourly fan consumption (kW)
$\Delta E_{heating}$	Hourly energy savings during winter operation (kW)
ΔE_{total}	Total hourly energy savings (kW)
ΔP	Pressure difference, kPa
ΔT	Air stream temperature difference across the OHP-HRV (°C)
$\Delta Cost_{cooling}$	Hourly cost savings while cooling ($)
$\Delta Cost_{heating}$	Hourly cost savings while heating ($)
$\Delta Cost_{el}$	Electricity cost for each location (cent/kW h)
$\Delta Cost_{ng}$	Natural gas cost for each location ($/28316.8 L) or ($/1000 cu. ft.)

Greek symbols

δ_l	Film thickness (m)
ε	OHP-HRV effectiveness
$\eta_{surface}$	Surface efficiency of outer surface of OHP tube
$\eta_{furnace}$	Furnace efficiency
μ	Dynamic viscosity (N s/m^2)
ν	Kinematic viscosity (m^2/s) or specific volume of air (m^3/kg)
ρ	Density (kg/m^3)
σ	Surface tension (N/m)
σ_f	Ratio of free-flow area to frontal area

Subscripts

1	Before heat exchanger
2	After heat exchanger
c	Condenser
c, in	*Cold air stream at inlet*
D	Diagonal
drive	Fan belt drive
f	Fin
fan	Fan
h	Evaporator
h, in	Hot air stream at inlet
i	Internal
in	Into heat exchanger
l	Liquid
L	Longitudinal
m	Mean
max	Maximum
min	Minimum
motor	Fan motor
o	Outside/overall
out	Out of heat exchanger
req	Required
S	Transverse
v	Vapor
w	Wall

HP-HEs have been investigated for their application in HVAC systems (Abd El-Baky and Mohamed, 2007; Yau and Tucker, 2003; Lamfon et al., 1998; Liu et al., 2006; Jouhara and Meskimmon, 2010). These devices are typically made of copper or aluminum (Roth, 2012) and comprise of multiple conventional-type heat pipes (CHPs) bundled together. In general, the HP-HE operating at an effectiveness of 50%–80% results in a pressure drop of 100–500 Pa for a face velocity of 400 to 800 fpm (Roth, 2012). The CHP is a two-phase heat transfer device that operates in a passive, cyclic manner (Grover and Chrisman, 1987). The device is partially filled with a pre-selected amount of working fluid (i.e. water, refrigerant, etc.) quantified via a 'fill ratio'. The prominent design of the CHP is its wicking structure (coaxial grooves, sintered particles) along its internal periphery (Peterson, 1994). During operation, liquid evaporates near the heat source (evaporator) causing vapor to flow toward the heat rejection site (condenser), where the vapor condenses and then returns to the evaporator as liquid via wicking and/or gravity. A CHP's thermal performance can be influenced by its operating orientation, and for a given design and working fluid combination, several operational limits can exist, such as the entrainment, sonic and boiling limitations (Peterson, 1994).

The oscillating heat pipe (OHP) is another type of two-phase heat transfer device; however, unlike the CHP, the OHP does not need an internal wicking structure to operate effectively. The OHP typically consists of a closed-loop, capillary structure (tube or channel) that meanders to and through a heat reception and rejection site forming multiple 'turns' (Khandekar and Groll, 2004). The OHP is partially filled with a working fluid and its internal

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