Heat Transfer Analysis and Experiments with Energy Recovery Ventilator

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Abstract— **A numerical and experimental study has been carried out for a rotary, periodic flow energy recovery ventilator containing a porous media matrix. The governing differential equations for heat transfer have been solved using an upwind integral-based method. The influence of the matrix material characteristics on the effectiveness and performance of the energy recovery ventilator is analyzed. It is shown that the numerical and analytical results compare well with experimental data.**

Index Terms— **heat exchanger, porous matrix, energy recovery ventilator, sensible effectivness.**

I. INTRODUCTION

Residential and commercial buildings rely on outdoor ventilation to keep the concentration of indoor-generated pollutants at a low level and to maintain acceptable indoor air quality. However, typical ventilation process implies higher energy costs required to condition (heat or cool, humidify or dehumidify) the entering outdoor air.

Energy recovery ventilators (ERV) can reduce air-conditioning costs in ventilated buildings by recovering the energy from the outlet air stream and transferring it to the inlet air stream. These ventilators are heat exchanger units that are produced in different configurations. In a rotary, periodic heat recovery ventilator (Fig. 1), heat is transferred from the hot fluid to a solid matrix during one half of the revolution and from the solid matrix to the cold fluid during the second half of the revolution. The matrix rotates from one air stream to the other cyclically to provide continuous heat transfer.

The ERV in this study has been investigated by Druma and Alam [1]-[2] to determine the heat transfer and efficiency. In the present study, the results from prior studies are compared with results obtained by Shah [3]. In Shah's approach the heat transfer in rotary heat exchangers is analyzed by using $\varepsilon - NTU$ method to predict the performance of these units. This is an extremely useful analytical method; however, the effect of mass transfer (moisture in the air stream) and material property variation can not be included in this approach.

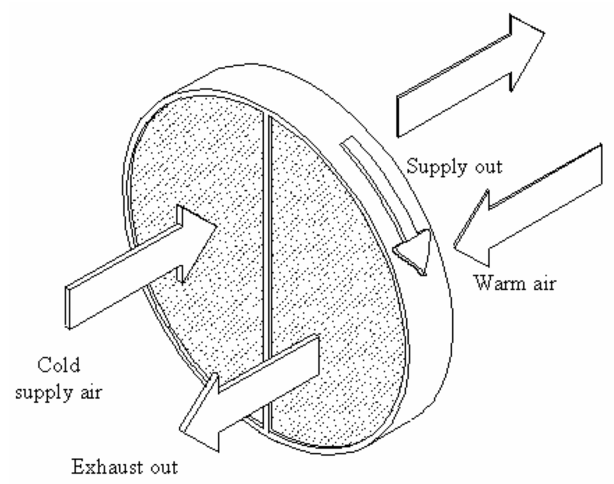

Fig. 1. Energy wheel [1]

It is desirable for the ventilators to transfer moisture as well as heat energy to maintain the indoor humidity level. Several newer ventilators are being equipped with desiccant coated matrix to enhance moisture recovery. Simonson and Besant [4]–[6] published a series of papers in which they included the mass transfer of moisture in rotary ERVs. The objective of this study is to study the effectiveness of a rotary, periodic flow ERV with a porous media as the heat exchanger medium. In this paper, a numerical algorithm based on an integral approach has been developed to calculate the heat transfer in the ERV. This approach can be used to study the moisture transport (mass transfer) along with heat transfer. The numerical analysis has been applied to an ERV using a fibrous porous media as the heat exchanger core. The combined heat and mass transfer study is currently in progress.

Experiments were carried out for the ERV that was subject of this numerical analysis. The sensible effectiveness, i.e., the effectiveness of the ERV on the basis of inlet and outlet temperatures is then compared with the numerical results and with the $\varepsilon - NTU$ method.

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II. NOMENCLATURE

A cross-sectional area [m^2]
Cp specific heat [Jkg^{-1}K^{-1}]
D diameter of the wheel [m]
d_f diameter of the fiber [m]
h convective heat transfer coefficient [Wm^{-2}K^{-1}]
k thermal conductivity [Wm^{-1}K^{-1}]
L Thickness of the wheel
Nu Nusselt number
Pr Prandl number
Re Reynolds number, $\mathrm{Re} = \dfrac{\rho_g U_D d_f}{\mu_g (1-\varphi)}$
t time [s]
T temperature [K]
U mean air flow velocity [ms^{-1}]
x axial coordinate [m]

Greek symbols

ρ density [kgm^{-3}]
φ porosity of the matrix

Subscripts

m matrix
g gas phase
c surface area for convection
co cold
h hot

III. THEORY

For this initial phase of the study, and for comparison with the ε *-NTU* method, the governing differential equations were solved for the heat transfer process only, neglecting the mass transfer terms.

The governing differential equation to calculate the temperature of the gas (neglecting the mass transfer) is given by [1-2]:

$$\rho_g A_g Cp_g \frac{\partial T_g}{\partial t} + h\frac{A_c}{L}\left(T_g - T_m\right) + \frac{\partial}{\partial x}\left(\rho_g U A_g Cp_g T_g\right) = 0 \quad (1)$$

The governing differential equation to calculate the temperature of the matrix (neglecting the mass transfer) is given by:

$$\rho_m Cp_m A_m \frac{\partial T_m}{\partial t} - h\frac{A_c}{L}\left(T_g - T_m\right) = k_m A_m \frac{\partial^2 T_m}{\partial x^2} \quad (2)$$

The cross sectional areas in the equations above, A_g, A_m, A_c, are functions of the porosity of the matrix, the diameter of the fiber, and the diameter of the energy wheel. Therefore they can be expressed as:

$$A_g = \frac{\pi\varphi D^2}{8}$$

$$A_m = \frac{\pi(1-\varphi)D^2}{8}$$

$$A_c = \frac{\pi(1-\varphi)LD^2}{2d_f}$$

The convective heat transfer coefficient is calculated with the following equation [7]:

$$h = \frac{Nu\, k_g (1-\varphi)}{d_f \varphi}$$

The Nusselt number *Nu*, has been defined as:

$$Nu = 2 + \left(0.4\,\mathrm{Re}^{1/2} + 0.2\,\mathrm{Re}^{2/3}\right)\mathrm{Pr}^{0.4}$$

For the material properties specific to this case it has been found that the convective heat transfer coefficient is approximately 200 W/m^{2}K.

IV. BOUNDARY CONDITIONS

The boundary conditions for the three differential equations used to model the system are the hot and cold side air stream temperatures. The boundary conditions shown below are applied cyclically for each side as the matrix rotates through the cycle [1]:

Hot side

$$T_g(x=0) = T_h$$

Cold side

$$T_g(x=L) = T_{co}$$

It will be assumed that the axial conduction heat transfer at the entrance and exit of the wheel is negligible compared to the heat transfer inside the matrix. Therefore the end cross-sectional surfaces of the matrix are considered to be insulated:

$$\left.\frac{\partial T_m}{\partial x}\right|_{x=0} = \left.\frac{\partial T_m}{\partial x}\right|_{x=L} = 0;$$

The governing equations along with the boundary conditions are solved numerically by an integral numerical method. Tsai et al [8] have shown that this integral approach produces accurate results for pure advection and advection-diffusion equation. The stability of the integral method presented above was verified using the discrete perturbation method [9].

V. RESULTS AND CONCLUSIONS

A rotary heat exchanger was simulated with the thickness of the porous mesh fixed at 4 cm. The porosity of the mesh was 93.4%, and the flow rate was 200 cubic meters per hour. The ERV wheel speed was fixed at 28 RPM. These are representative parameters for a system on which future experiments were carried out. Numerical simulations were carried out for different porosities of the matrix and for different wheel rotation speeds. The effectiveness with respect to different porosities of the heat exchanger material and with respect to different rotational speeds of the wheel has been plotted and presented in Fig. 2 and Fig. 3 respectively.

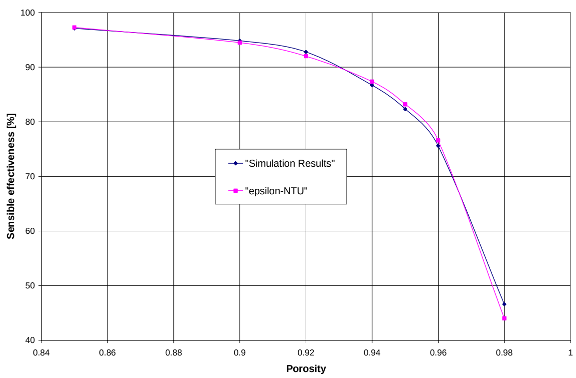

Fig. 2. Variation of sensible effectiveness with the porosity of the heat exchanger material

In Fig. 2 can be seen that the numerical simulation values [2] are very close to the results predicted by the $\varepsilon - NTU$ analysis of Shah [3]. The sensible effectiveness is the effectiveness based on the inlet and outlet temperatures without consideration of the moisture transfer effects on energy transport. From Fig. 3 one can conclude that the sensible effectiveness of the rotary heat exchanger increases with the increase of the rotational speed to a maximum value of about 90%. It should be noted that, unlike the $\varepsilon - NTU$ approach, the numerical simulation could be extended to the case of heat and mass transfer. The issue of moisture transfer in the ERV is currently being studied using the numerical simulation described above.

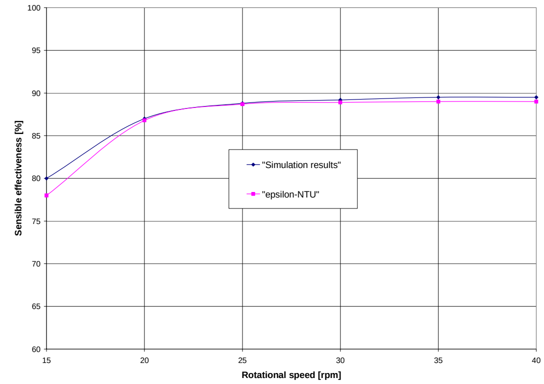

Fig. 3. Sensible effectiveness dependence with rotational wheel speed

Experiments were also carried out along with numerical simulations of the rotary heat exchanger with a porous matrix. In the experiments, the thickness of the porous mesh was 4 cm. A 93.4% porous mesh was tested, and the flow rate was 200 cubic meters per hour.

The effectiveness was determined at steady state conditions during the experiments. To compare the experimental results with theory, the numerical simulation was run for different boundary conditions. The results are compared in Table I. It can be seen from this table that the $\varepsilon - NTU$ method provides identical results for all boundary conditions since this analysis does not include the effect of temperature in the flow stream. However, the experimental value of the effectiveness of the rotary heat exchanger is close to the value predicted by Shah [3] and by the numerical simulations.

Table I

Simulation results and comparison with experiments and the $\varepsilon - NTU$ method				
Supply air Temperature [K]	Exhaust air Temperature [K]	ε exp. [%]	ε (ε-NTU) [%]	ε Integral Method [%]
$T_{g\,co,o}$=267	$T_{g\,h,i}$=287	89.6	89.1	88.7
$T_{g\,co,o}$=270	$T_{g\,h,i}$=298	87.8	89.1	88.8
$T_{g\,co,o}$=276	$T_{g\,h,i}$=294	88.3	89.1	88.75

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