Air-to-Air Fixed Plate Energy Recovery Heat Exchangers for Building's HVAC Systems

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The provision of fresh outdoor air to buildings has become a legislated standard practice in many countries around the world to improve indoor air quality. However, in HVAC systems the cost of conditioning the outdoor air is very high. For such systems, it is essential to utilize energy recovery devices to reduce this load. Therefore, air-to-air fixed plate heat exchanger is used in buildings where the room exhaust air is passed in one stream and ambient fresh air is passed in the other stream of the heat exchanger. This heat exchanger has two types which are: sensible heat exchanger which recovers only sensible heat and enthalpy heat exchanger which utilizes membrane and recovers both sensible and latent heat (dehumidify the supplied air). This heat exchanger will precondition the fresh air prior to supplying the air to an air conditioner resulting in substantial amount of energy saving.

Introduction

In the last few decades, building indoor air quality has become a great concern which is affected by volatile organic compounds, smoke, dust, and bacteria. As a result, many countries in the world have adopted new standards that specify higher indoor quality in buildings [1]. ASHRAE Standard 62 [2] defines acceptable indoor air quality as air in which there are no known contaminants at harmful concentrations and that a substantial majority of people exposed do not express dissatisfaction. Maintaining thermal comfort is not just desirable in assuring a productive work environment, but in many cases also has a direct effect on the health of the occupants.

Previous research showed that for an outdoor ventilation rate of 40%, the heating load would increase by around 30% as compared to no outdoor ventilation [3]. In

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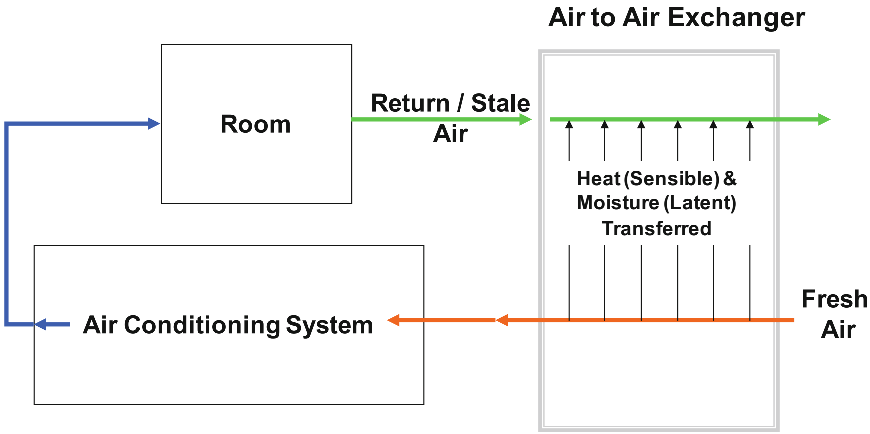


Fig. 1 Operating principle of air-to-air fixed plate exchanger

addition, the fresh air is a major source of moisture and will cause an increase in the latent load in the air-conditioning system. In fact, the latent load constitutes a large fraction of the total thermal load for an air-conditioned building. This latent load would increase when 100% fresh air is used in certain buildings, especially in a humid climate. Normally the water vapor in atmospheric air is small (some tens of grams per kilogram of fresh air), however, due to the high heat of vaporization, the latent load on an HVAC system constitutes a large fraction of the total thermal load. In addition, any excessive moisture content in a building must be dealt with by the HVAC system, as this moisture can lead to mold growth (particularly in humid climates) and indoor air quality problems [4].

There is a strong link between indoor air quality, temperature, humidity, and occupant productivity. However, meeting the minimum ventilation requirements may not be in the best interest of the building owner/operator, due to increased operating cost. Therefore, with energy costs rising, building owners and operators are looking for ways to conserve energy and lower utility bills using energy recovery systems.

Air-to-air fixed plate energy recovery system is one method proven to reduce energy consumption. This can be achieved by utilizing the room exhaust air to pre-cool or heat the fresh air before it enters the air-conditioning system as depicted in Fig. 1. Such systems reduce the HVAC operating cost.

Types of Fixed Plate Heat Exchangers

In general, there are two types of air-to-air energy recovery heat exchanger. The first type is the rotary wheels which require a motor to rotate the wheel. It does not provide 100% fresh air because of air carry over between the two streams. The second type

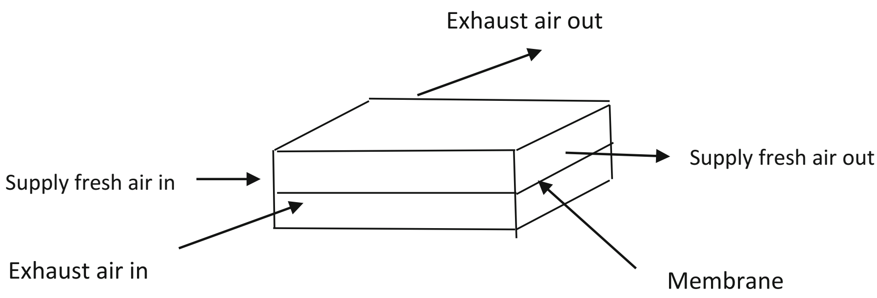


Fig. 2 Cross-flow air-to-air fixed plate exchanger

is fixed plates air-to-air heat exchanger. This exchanger is a static device that can be integrated into existing HVAC systems with minimum leakage between streams. It is less bulky than other energy recovery devices and has no complicated mechanisms and does not transfer dust and pollutants. Furthermore, it is cheap, does not require maintenance and external power to drive them, and it is simple to construct and safe to use in any ventilation system.

Energy recovery systems are classified into two categories, which are sensible and latent heat recovery. They are available as sensible heat exchangers and enthalpy heat exchangers, in which the designs are the same for both types of heat exchanger.

Sensible Fixed-Plate Heat Exchanger

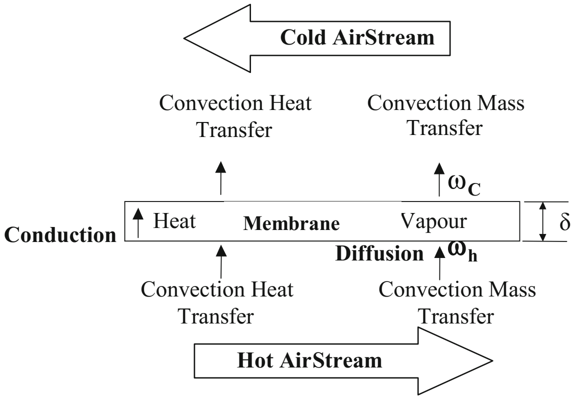
The fixed-plate sensible heat exchanger consists of alternate layers of frames (which are known as flow paths). These layers form the supply and exhaust air stream passages, and these streams are separated by thin plates or plastic sheet.

The flow path allows the fresh and humid air to flow into the frames, whereas, the cold less humid air flows through the alternate frames which are laterally inverted with the fresh airframes. A thin plastic or metal sheet is used as a heat transfer surface between the two streams. Hence, only sensible heat will be transferred. The heat exchanger could be designed to provide cross-flow, or quasi-counter flow arrangement. Figure 2 shows cross-flow configuration of the heat exchanger.

Enthalpy Fixed Plate Heat Exchanger

This heat exchanger was developed with the first prototype tested unit in the year 1970 [5] and was developed due to the increase in demand to recover latent heat and to overcome the disadvantages and limitations of other energy recovery devices. In fact, it is an enhanced version of the sensible fixed-plate heat exchanger where

Fig. 3 Heat and moisture transfer across the membrane



conventional plates are replaced by a permeable material (such as membrane) that is able to transfer both heat and moisture.

The operation of membrane-based enthalpy heat exchangers is based on the second law of thermodynamics which states that energy always transfers from a region of high temperature to one of a low temperature. This law can be extended to say that mass transfer always occurs from region of high vapor pressure to one of low vapor pressure through a permeable material.

In fact, both heat and mass transfer phenomena influence membrane-based enthalpy energy recovery systems, where the ambient hot and humid supply air is passed over one side of a membrane heat exchanger and on the other stream the cold and less humid air is passed. Due to the gradient in the temperature and vapor pressure concentration, heat and moisture are transferred across the membrane surface.

The heat and moisture are transported from the hot and humid stream to the membrane surface by convection, followed by conduction of heat and diffusion of moisture through the porous membrane surface and by convection from the membrane surface to the cold and less humid stream, causing a decrease in temperature and humidity of the supply air stream before it enters the evaporator unit, hence both sensible and latent energy are recovered as shown in Fig. 3.

Heat Exchanger Performance

The performance of the heat exchanger is usually evaluated by calculating the heat exchanger sensible, latent and total effectiveness, where, the effectiveness represents the ratio between the actual heat transfer rate and the maximum heat transfer rate. The sensible heat transfer represents the amount of heat transferred due to temperature difference; latent heat transfer represents the amount of latent heat transferred due to moisture content difference (vapor pressure difference); and total heat transfer represents the amount of total heat transferred due to the enthalpy difference between the heat exchanger streams. The heat exchanger effectiveness can be determined through experimental measurements and mathematically by using Effectiveness-NTU method.

Effectiveness from Experimental Measurements

Through measuring the air inlet and outlet conditions (temperature and humidity), the general form of the sensible effectiveness is:

$$\varepsilon_S = \frac{\dot{m}_s C_p (T_{\text{hi}} - T_{\text{ho}})}{\dot{m}_{\min} C_p (T_{\text{hi}} - T_{\text{ci}})} = \frac{\dot{m}_e C_p (T_{\text{co}} - T_{\text{ci}})}{\dot{m}_{\min} C_p (T_{\text{hi}} - T_{\text{ci}})} \tag{1}$$

Analogous to the sensible effectiveness, the latent effectiveness is calculated based on the amount of moisture transferred and is represented by:

$$\varepsilon_L = \frac{\dot{m}_s h_{\text{fg}} (\omega_{\text{hi}} - \omega_{\text{ho}})}{\dot{m}_{\min} h_{\text{fg}} (\omega_{\text{hi}} - \omega_{\text{ci}})} = \frac{\dot{m}_e h_{\text{fg}} (\omega_{\text{co}} - \omega_{\text{ci}})}{\dot{m}_{\min} h_{\text{fg}} (\omega_{\text{hi}} - \omega_{\text{ci}})} \tag{2}$$

and the total effectiveness is expressed as:

$$\varepsilon_{\text{tot}} = \frac{\dot{m}_s (H_{\text{hi}} - H_{\text{ho}})}{\dot{m}_{\min} (H_{\text{hi}} - H_{\text{ci}})} = \frac{\dot{m}_e (H_{\text{co}} - H_{\text{ci}})}{\dot{m}_{\min} (H_{\text{hi}} - H_{\text{ci}})} \tag{3}$$

where $\dot{m}$ is air mass flow rate, $T_{\text{hi},}$ $\omega_{\text{hi},}$ and H_{hi} are ambient air inlet temperature, humidity ratio, and enthalpy, T_{ho}, $\omega_{\text{ho},}$ and H_{ho} are air outlet temperature, humidity ratio, and enthalpy which enters the cooling coil, T_{ci}, $\omega_{\text{ci},}$ and H_{ci} are room exhaust air temperature, humidity ratio, and enthalpy, and h_{fg} represents air enthalpy of evaporation.

From the above equations, it is clear that the ideal energy transfer would move 100% of the energy difference between the stream with the higher temperature and humidity to the stream with lower temperature and humidity. From the above equations too, the sensible and enthalpy heat exchanger performances are determined.

Effectiveness-NTU Method

To determine the sensible and latent effectiveness, two mathematical models must be used. The sensible model is detailed as follows, in which the sensible heat transfer model is based on Nusselt number and Reynolds number correlations for each air channel.

When the Reynolds number is less than 2000, Hausen's correlation is recommended for laminar flow in ducts under uniform heat flux [6]. The correlation includes flow developing effect in heat exchangers:

$$\mathrm{Nu} = 8.235 + \frac{0.0068\left(\mathrm{d_{hy}}/\mathrm{L}\right)\mathrm{Re\,Pr}}{1 + 0.04\left[\left(\mathrm{d_{hy}}/\mathrm{L}\right)\mathrm{Re\ Pr}\right]^{2/3}} \tag{4}$$

where d_{hy} is the hydraulic diameter, L is the developed length. When the flow is turbulent the following correlation is used [6]:

$$\mathrm{Nu} = 0.036\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{\frac{1}{3}}\left(\frac{d_{\mathrm{hy}}}{L}\right)^{0.055} \tag{5}$$

The Reynolds number of a flow is calculated as:

$$\mathrm{Re} = \frac{V d_{\mathrm{hy}}}{\nu} \tag{6}$$

where V is the air velocity and ν is the kinematic viscosity. The Prandtl number, Pr, in Eq. (5) represents the ratio of fluid molecular diffusivity and molecular diffusivity of heat. By determining the Nusselt number from correlations above, the convective heat transfer coefficient (h_{heat}) is calculated:

$$h_{\mathrm{heat}} = \frac{\mathrm{Nu}\lambda}{d_{\mathrm{hy}}} \tag{7}$$

where the Nusselt number, Nu, represents the convective heat transfer through a fluid layer relative to the conduction across the same layer.

The total number of transfer units is:

$$\mathrm{NTU}_s = \frac{A_{\mathrm{ht}} U_s}{C_{\min}} \tag{8}$$

where A_{ht} is the area of heat transfer, and the heat capacity of the stream is:

$$C = \dot{m} C_p \tag{9}$$

where $\dot{m}$ is air mass flow rate, and C_p is air specific heat. The general form of overall sensible heat transfer coefficient, U_s, is:

$$U_s = \left[\frac{1}{h_{h,\,\mathrm{heat}}} + \frac{\delta}{k_{\mathrm{ther}}} + \frac{1}{h_{c,\,\mathrm{heat}}}\right]^{-1} \tag{10}$$

The thermal resistance (δ/k_{ther}) represents the conduction resistance of this heat transfer surface sheet and is a function of the material type and thickness. However, this term is very small due to the small thickness of the heat transfer film. The other two terms are the convective heat transfer resistance in the two streams, and these terms contribute the largest portion of the sensible heat transfer resistance (U_s).

The sensible effectiveness for cross-flow is:

$$\varepsilon_{s,\,\text{cross}} = 1 - \exp\left\{\frac{\text{NTU}_s^{0.22}}{\frac{C_{\text{min}}}{C_{\text{max}}}}\left[\exp\left(-\frac{C_{\text{min}}}{C_{\text{max}}}\text{NTU}_s^{0.78}\right) - 1\right]\right\} \tag{11}$$

Latent heat transfer model that simulates moisture transfer can be developed using the convective mass transfer Sherwood correlation. The convective mass transfer coefficient can be obtained using the Chilton-Colburn analogy [7]:

$$\text{Sh} = \text{Nu.Le}^{-\frac{1}{3}} \tag{12}$$

where Sherwood number (Sh) represents the convective mass transfer through a fluid layer relative to the mass diffusion across the same layer. Sherwood number is represented by

$$\text{Sh} = \frac{h_{\text{mass}} d_{\text{hy}}}{D_{\text{va}}} \tag{13}$$

The Nusselt and Sherwood numbers represent the effectiveness of convective heat and mass convection at the surface, respectively.

The Lewis number represents the relative magnitudes of heat and mass diffusion in the thermal and concentration boundary layers and is defined as:

$$\text{Le} = \frac{K_{\text{air}}}{C_{p\,\text{moist air}}\ D_{\text{water-air}}\ \rho_{\text{moist air}}} \tag{14}$$

By substituting Eq. (12) for Nusselt number and Eq. (14) into Eq. (13), the convective mass transfer coefficient (h_{mass}) can be represented by:

$$h_{\text{mass}} = \frac{h_{\text{heat}}}{C_{\text{pa}}}\text{Le}^{-\frac{1}{3}} \tag{15}$$

During the moisture transfer measurement in this study steam was injected into the hot stream in order to increase the vapor pressure, and thus, the Lewis number is typically 0.81 [8]. The number of latent energy transfer units (NTU_L) is:

$$\text{NTU}_L = \frac{A_{\text{ht}} U_L}{\dot{m}_{\text{min}}} \tag{16}$$

The overall mass transfer coefficient (U_L) is given by:

$$U_L = \left[\frac{1}{h_{h,\text{mass}}} + R_{\text{paper}} + \frac{1}{h_{c,\text{mass}}}\right]^{-1} \tag{17}$$

The moisture resistance of the porous material is $R_{\text{paper,}}$ and the other two terms are the convective mass transfer resistance of each flow stream. Researchers found that contrast to the membrane conduction thermal resistance which is almost constant, the membrane surface moisture transfer resistance varies with the humidity ratio difference across the paper surface [8].

In general, membranes have been classified into three categories according to the membrane moisture resistance variation under different humidity conditions. The first type is a membrane with constant moisture transfer resistance, where researchers found that the moisture resistance is independent of the air humidity. The second is a membrane with moisture resistance increasing in line with increasing the humidity. For this type of membrane, researchers found that the membrane moisture uptake decreases when the humidity increases. The third type is where the membrane moisture uptake increases when the humidity increases and subsequently the moisture resistance decreases with increasing the humidity [9]. To calculate the cross-flow latent performance, the latent effectiveness is represented as:

$$\varepsilon_{L,\,\text{cross}} = 1 - \exp\left\{ \frac{\text{NTU}_L^{0.22}}{\frac{\dot{m}\text{min}}{\dot{m}\text{max}}} \left[\exp\left(-\frac{\dot{m}\text{min}}{\dot{m}\text{max}} \text{NTU}_L^{0.78} \right) - 1 \right] \right\} \tag{18}$$

Energy Saving

Several studies were performed to investigate the energy saving fixed plate heat exchanger can provide. Nasif et al. [10] studied the annual energy consumption of an air conditioner coupled with an enthalpy/membrane heat exchanger and compared with a conventional air-conditioning cycle using in-house modified HPRate software. The heat exchanger effectiveness is used as thermal performance indicator and incorporated in the modified software. Energy analysis showed that an air-conditioning system coupled with a membrane heat exchanger consumes less energy than a conventional air-conditioning system in hot and humid climates where the latent load is high. It has been shown that in humid climate a saving of up to 8% in annual energy consumption can be achieved when membrane heat exchanger is used instead of a conventional HVAC system.

Nasif [11] investigated the performance of air-to-air fixed plate energy recovery heat exchanger utilizing porous paper and Mylar film as the heat and moisture transfer media used in ventilation energy recovery systems. This performance is represented by the heat exchanger sensible and latent effectiveness. A simplified air-conditioning system which is represented by cooling coil that incorporates air-to-air fixed plate heat exchanger to cool office space is developed under humid inlet air conditions. Energy analysis for tropical climate shows that utilizing paper surface heat exchanger in a standard air-conditioning system will lead to 78% energy saving as compared with utilizing Mylar plastic film which recovers only sensible heat.

These results show the significant contribution of the enthalpy heat exchanger in reducing the latent load in hot and humid climates, and the substantial energy savings achieved in comparison with conventional air-conditioning systems. In addition, enthalpy heat exchanger has the advantage of providing 100% fresh air.

Summary

Air-to-air fixed plate energy recovery exchanger is a static device which recovers substantial energy whilst providing 100% fresh air supply through HVAC systems. The performance of the heat exchanger can be calculated through determining the effectiveness. The effectiveness also can be predicted by using effectiveness-NTU method; however, the latent effectiveness requires determining the membrane moisture transfer resistance which its value changes according to the inlet air humidity.

Air-to-air fixed plate exchanger is a simple static device which requires less maintenance and can be easily integrated into HVAC system as compared to other energy recovery systems. Past research showed that air-to-air fixed plate membrane energy recovery performed very well and recovered high energy in humid climate as compared to moderate and dry climate conditions.

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