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AIR-TO-AIR HEAT EXCHANGERS: SAVING ENERGY AND IMPROVING INDOOR AIR QUALITY

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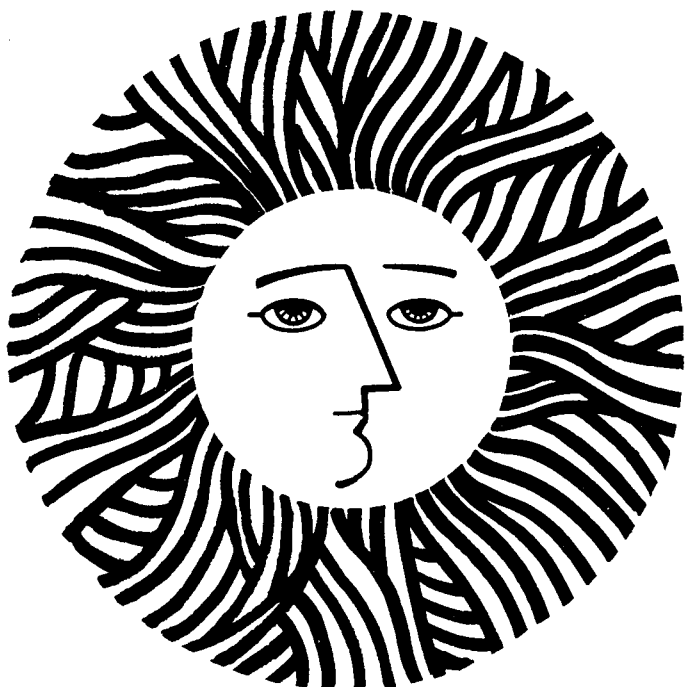

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ABSTRACT

Some houses currently built have substantially reduced air infiltration rates to conserve heating and cooling energy use. Indoor air quality problems associated with this large reduction in ventilation air have become apparent. This paper describes the use of mechanical ventilation coupled with heat recovery devices in residential buildings to maintain acceptable indoor air quality and conserve energy. Estimates of energy and peak power savings are given.

keywords: energy conservation, heat exchanger, indoor air quality, peak power

INTRODUCTION

About 15% of the total energy consumed in the U.S. is used for space conditioning in residential structures. The two major modes of heat loss or gain in a residential structure are the conduction of heat through the walls, windows, ceiling, and floor, and the natural infiltration of outside air through the structure. After a house has been reasonably well insulated, the natural infilration of outside air into the structure can become the largest mode of heat gain or loss. Houses in the U.S. have natural infiltration rates on the order of one air change per hour (ach) [1]. In a house with a floor area of 1500 ft.^{2} and a ceiling height of 8 feet, this means that 200 cubic feet per minute (cfm) of outside air must be conditioned by the home heating or cooling system in order to provide comfort to the occupants. Uncontrolled natural infiltration of outside air places an additional load on the home space conditioning system, and causes uncomfortable drafts.

A number of energy conserving homes have been constructed in Europe, Canada, and the U.S., having natural infiltration rates on the order of 0.2 ach or less. These low infiltration rates have been achieved through the use of tight-fitting windows and doors, and the installation of a plastic air/vapor barrier in the ceilings, walls, and floors of the structures [2]. This air/vapor barrier is normally unpenetrated by electrical wiring or plumbing or, if penetrated, it is sealed so that air cannot leak through the junction.

Indoor air quality problems associated with a large reduction in ventilation have been recognized [3,4,5]; these include: excessive humidity levels, increased and longer lasting odors from human activities, and increased levels of chemical contaminants, e.g., formaldehyde and radon gas in the indoor air.

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HEAT EXCHANGERS AND INDOOR AIR QUALITY

One method of alleviating these problems is to introduce a mechanical ventilation system into a nearly air-tight house and thereby ventilate in a controlled manner. An air-to-air heat exchanger installed in the mechanical ventilation system can save a substantial amount of energy by preheating or precooling the incoming outdoor air to a temperature closer to the inside conditions.

In a mechanical ventilation system with a heat exchanger, two small "balanced" fans are used. One fan brings in outside air for ventilation while the other exhausts an equal amount of indoor air to the outdoors. These two air streams are brought into close proximity with one another inside the air-to-air heat exchanger. Inside the heat exchanger the exhaust and fresh air streams are separated by thin sheets of aluminum, plastic, or treated paper, which should not allow mixing of the two air streams. Heat is transferred from the hot to the cold air stream by forced and natural convection, and by conduction through the material that separates the air streams. One commercially available heat exchanger [6] allows for latent heat transfer through the use of a permeable, treated paper, heat transfer surface.

Mechanical ventilation units with heat exchangers sized for residential use are currently being manufactured in Europe, Japan, and Canada. A Japanese company reported sales of 65,000 units in 1977, and one of many European companies reports sales of 4300 units in 1978, and is projecting sales of 8000 units for 1979. Prices vary widely, from about $140 for a small window type unit up to $2500 for an installed central mechanical ventilation system that takes exhaust air from the bathrooms and kitchen and supplies fresh air to the living room and bedrooms.

The Lawrence Berkeley Laboratory (LBL) began a program in October of 1978 to examine the use of mechanical ventilation units with air-to-air heat exchangers in residential buildings in the United States. The program consists of four parts:

- Analysis and experimental evaluation of air-to-air heat exchangers;
- Testing of a mechanical ventilation system utilizing an air-to-air heat exchanger in the LBL research house;
- A cost-benefit analysis of these systems operating in different climate zones of the U.S.;
- Installation and testing of a number of systems in occupied homes.

Energy savings, indoor air quality and different modes of operation will be investigated.

The heat exchanger performance data generated by this project will be combined with appropriate climatological and economic parameters, in order to develop an economic model evaluating life-cycle costs of heat exchanger utilization in single family dwellings. Results will be assessed against baseline data from "typical" single family dwellings in the same environment. Returns on investment and payback periods will be estimated for various commercial heat exchangers operating in different environments.

HEAT EXCHANGERS: ENERGY AND PEAK POWER SAVINGS

DOE-2 [7], LBL's public-domain computer program for energy analysis of buildings, was used to calculate the expected energy savings for single family homes employ-

ing mechanical ventilation and heat exchangers (MV/HE). For the purpose of these calculations the base case house is a double glazed, 1500 ft^2 floor area, single story detached home with R38 ceiling, and R19 wall, insulation [8].

The calculations were carried out for this house operated in three different ventilation modes in four selected United States cities. In the first mode, 0.75 ach represents the ventilation occurring naturally under average year-round temperature and weather conditions. For the two other modes ("tight" house), only 0.2 ach is assumed to occur naturally (under the same average weather and temperature conditions) and an additional 0.3 or 0.55 ach of controlled air flow is vented through a heat exchanger with a sensible heat transfer efficiency of 75%. Therefore, these "tight" houses actually have a total of 0.5 or 0.75 ach but lose heat to the outside air as if they had infiltration rates of 0.275 and 0.338 ach, respectively. The infiltration rate is computed from a Coblentz-Achenbach equation [9] with coefficients used by the National Bureau of Standards*. For the base case, the air changes per hour are given by the Coblentz-Achenbach relation

$$\text{ach} = 0.315 + 0.0273V + 0.0105\ |T_A - T_R|, \tag{1}$$

where V is the wind speed in miles per hour; and T_A and T_R are the ambient and room temperatures in degrees Fahrenheit. For average winter conditions in Chicago, this equation yields 0.93 ach. For the tight house with 0.55 ach of controlled air flow, the actual air changes per hour are

$$\text{ach (actual)} = 0.63 + 0.0073V + 0.0028\ |T_A - T_R|, \tag{2a}$$

and the thermal equivalent, including the 75% efficiency of the heat exchanger, is

$$\text{ach (thermal)} = 0.22 + 0.0073V + 0.0028\ |T_A - T_R|. \tag{2b}$$

Energy Savings in Winter

Table I illustrates the yearly loads (in MBtu) for heating outside air in the three different ventilation modes described above in four selected United States cities. Also shown in this table are the differences in energy use when the two low infilration houses are compared to the high infiltration base house. Houses with total ventilation rates of both 0.5 and 0.75 ach have been included, since at this time the ventilation rate sufficient to maintain adequate indoor air quality is not known, but it is believed that at least 0.5 ach is required [10]. The heating degree days (base temperature 65°F) for the four cities are shown for informational purposes.

Table II shows the energy costs savings in dollars for houses with various types of heating systems. The prices of electricity, gas and oil are assumed to be \$11.80, \$3.10 and \$4.00 per million Btu, respectively, throughout the U.S. The dollar savings in Table II have already been corrected for the cost of running two 25-watt and two 45-watt fans for 3000 hours, for the 0.5 ach and 0.75 ach cases respectively. For new construction with central air conditioning and/or heating systems, the incremental cost of tightening a house and installing a heat exchanger would be about \$500.00. Therefore, for cold climates the payback period

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*The NBS coefficients were multiplied by 1.25 to simulate the existing housing stock, where 0.75 ach is taken to be the average year-round infiltration rate for all U.S. cities, rather than .6 ach, which corresponds to the measurements on the NBS Bowman house.

for heat exchanger installation as an energy conservation strategy would be a few years. If cooling season savings were appreciable, or if higher efficiency heat exchangers [11] could be utilized, payback times would decrease.

Table I — Outside Air Heating Load (MBtu)

City	Degree Days Base (65°F)	0.75 ACH (base case)	0.5 ACH*	0.75 ACH*	Energy Saved (MBtu) compared to base case .5 ACH	.75 ACH
Atlanta, Georgia	2961	15.82	5.80	7.13	10.0	8.7
Washington, D.C.	4224	23.09	8.46	10.41	14.6	12.7
Chicago, Illinois	5882	36.16	13.26	16.30	22.9	19.86
Minneapolis, Minn.	8382	57.17	20.96	25.76	36.2	31.41

*Total outside air of which .2 ACH is infiltration

Table II — Dollars Saved Over Heating Season* for Three Different Fuels

City	.5 ACH Oil	.5 ACH Gas	.5 ACH Electricity	.75 ACH Oil	.75 ACH Gas	.75 ACH Electricity
Atlanta, Georgia	34.0	25.0	112.0	24.0	16.0	92.0
Washington, D.C.	52.0	39.0	166.0	40.0	29.0	139.0
Chicago, Illinois	85.0	65.0	264.0	69.0	51.0	224.0
Minneapolis, Minn.	138.0	106.0	421.0	115.0	87.0	360.0

*Heating system efficiency taken to be 70% for gas and oil and 100% for electricity.

Peak Power Savings in Summer

In the U.S. residential sector, space heating consumes about 9 quads (1 quad is 10^{15} Btu), while air conditioning consumes only about 0.9 quads of resource energy; but air conditioning is the source of the summer peak in power demand, and therefore, a driving force in the construction of expensive new power plants, now costing about $1 per new kW available at the customer's meter.

Hence, the two important rewards for reducing infiltration are the saving of energy in the winter and peak power in the summer.

There is a second major difference between summer and winter use of heat exchangers; in winter it is most important to recover sensible heat, in summer, latent heat. In winter it is not important to recuperate indoor water vapor, but in summer, if an exchanger simply cooled damp, hot outdoor air, it would introduce an unacceptable stream of fog into the house. Specifically, air conditioners in southern and eastern climates devote 1/2 to 2/3 of their capacity to drying air, i.e., 1/2 to 2/3 of the infiltration load is a latent load. But a water-permeable heat exchanger can transfer most of this latent load from the incoming to the exhaust air stream, and is, therefore, 2 to 3 times more effective than a conventional exchanger in reducing cooling load [6]. One problem with the use of a permeable exchanger is that air contaminants, especially water-soluble species, may be transferred along with the water vapor. This problem needs further study.

Table III, columns 2 and 3, shows that tight houses will reduce peak electric loads in Miami by 485-610 Watts on a hot, windy afternoon. To make these estimates, we used our computer program "2-Zone" [12] to run a "base case" house through a Miami summer, using hourly Test Reference Year weather data.

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Table III Peak Power Required for Conditioning Outside Air for a 1500 ft^2 house in Miami at 6:00 p.m., July 14. The house conformed to 1977 California Standards.

	Average	Windy	Peak
1. Wind (mph)	10	15	20
2. Air Changes/Hour (Eq. 1)	0.7	0.85	1.0
3. Infiltration Cooling Loads from Line 2			
3a. Latent (KBtu/hr)	1.8	2.2	2.5
3b. Sensible (KBtu/hr)	4.8	5.8	6.9
3c. Total (KBtu/hr)	6.6	8.0	9.4
4. Internal Loads (KBtu/hr)	7.5	7.5	7.5
5. Envelope Loads (KBtu/hr)	3.6	3.6	3.6
6. Total a/c Load (KBtu/hr)	17.7	19.1	20.5
7. Reduced Infiltration (Eq. 2a)			
7a. ach (true) (Eq. 2a)	0.73	0.77	0.81
7b. ach (equivalent) (Eq. 2b)	0.32	0.36	0.4
7c. Cooling Load from line 7b (KBtu/hr)	3.04	3.38	3.76
8. Cooling Load Saved Lines 3c - 7c (KBtu/hr)	3.56	4.62	5.64
9. Watts Saved at EER = 8.0[a]	355	485	610

Notes a. EER (Electric Efficiency Ratio) is defined as Btu/hr (extracted) per electric Watt input. The 1979 Califonia standard is 8 for central a/c units. These savings have been reduced by the 90 Watts needed to run a balanced pair of fans handling 200 m^3/hrs.

The base case house conformed to the 1977 California standard for new residences (reasonably well insulated, and with a south overhang shading the windows). Its infiltration algorithm was Eq. (1); so it averaged 0.75 ach. Its daytime internal load (electricity plus occupants) averaged 1500 Btu/h (0.44 kW thermal), but rose to 7500 Btu/h at 6 p.m. The 2-zone output plots then show air conditioning demand peaking in mid-afternoon, but total electric demand peaking at 6 p.m.

Table III shows three columns, labelled for 10, 15, and 20 mph winds. We actually found several hot summer days with winds above 25 mph, and infiltration cooling loads greater than 10,000 Btu/hr (3 kW thermal). If air conditioners are sized to meet hot 20 mph winds then it is column 3 (labelled "peak") which describes heat loads and savings. If, however, we assume that most residential air conditioners are not sized to meet these rare peaks, then the more conservative situation is described in column 2, 15 mph ("Windy").

Turning to this conservative 15 mph column of Table III, we see a base-case infiltration of 0.85 ach, causing an air conditioning load of 8000 Btu/hr (2.3 kW), out of a total house air conditioning load of 19,000 Btu/hr.

How much of this 8000 Btu/hr can be saved by reduced infiltration? There are two approaches.

1. One can argue that although air should be changed in a house about once an hour, it need not be changed every hour on the hour; i.e., one should build a tight house with a heat exchanger, but turn it off (perhaps along with the air conditioner) when the electric utility is experiencing peak demand. Then the 8000 Btu/hr at 0.85 ach shrinks to ~2000 Btu/hr at 0.2 ach. This saves 6000 Btu/hr, which, at an EER of 8 yields an electric power savings of 750 Watts.

2. Or we can leave the heat exchanger fan running, at the constant rate of 0.55 ach (as in Eq. 2). Then Table III, line 7c, shows that the infiltration air conditioning load drops from 8000 to 3380 Btu/hr, saving about 4600 Btu/hr. At our EER of 8, the power saving is then 575 Watts before the fan power is subtracted.

Hence we conclude that in Miami we save 485-750 W. In Washington, D.C., the effects are 85-90% as great*.

Since the construction of new power plants costs an electric utility about $1 per peak, available Watt, we see that reducing infiltration saves the utility (and so eventually the rate payer) an investment of $500-750 in Miami. This then offsets the $500 cost of tightening a new house and installing a heat exchanger; so the energy savings in winter are pure profit.

In terms of power plant investment deferred nationwide by reduced infiltration, we note that if ~ 20 million houses in the hot damp parts of the U.S. each save 0.5 kW, the total peak reduction is 10GW, i.e., the reliable output of about 10-15 new standard power plants.

CONCLUSIONS

It appears that "air-tight" houses will require mechanical ventilation to assure adequate indoor air quality. A mechanical ventilation system coupled with an air-to-air heat exchanger can provide this outside air while recovering a large fraction of the heat that would otherwise be lost. Annual fuel savings during the heating season of about $100/year for oil in Minneapolis, about $50/year for gas in Chicago and hundreds of dollars for electric resistance heat have been shown. In addition, recovery of latent heat yields peak power savings of about 500 watts for Miami and Washington, D.C. houses. At utility construction costs of about $1/peak available watt this 500 watt savings pays for the cost of tightening the house and installing a heat exchanger in the first year. Of course, some pricing mechanism (incentives or residential peak power charges) must be found to transfer these utility savings to the home owner.

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*Table III, line 3c, shows an enthalpy of 9400 Btu per air change. In our Washington runs, on hot windy afternoons, we find typically 8300 Btu per air change in the same units, i.e., 88% as great as the enthalpy in Miami.

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