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Author

Fisk, W.J.

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William J. Fisk, Brian S. Pedersen,
Dariusch Hekmat, Raymond E. Chant, and Hossein Kaboli

Building Ventilation and Indoor Air Quality Program
Lawrence Berkeley Laboratory
University of California
Berkeley, California, 94720

July 1984

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ABSTRACT

Enthalpy exchangers are frequently employed to transfer heat and water between the supply and exhaust airstreams of mechanical ventilation systems. Concern has been expressed that some indoor-generated air pollutants, especially formaldehyde, may be transferred between airstreams by this type of heat exchanger and, thus, returned to the indoor space. This paper describes an experimental study in which the formaldehyde, tracer gas, and water vapor transfer rates in two enthalpy exchangers were measured. The first exchanger uses a crossflow core fabricated from a treated paper. The core of the second heat exchanger is a rotating heat wheel coated with lithium chloride. To reduce the transfer of gases by air leakage each core was installed in a specially fabricated case. Only 5% to 8% of the two tracer gases and 7% to 15% of the formaldehyde injected into the exhaust airstream was transferred to the supply airstream. Therefore, formaldehyde transfer between airstreams by processes other than air leakage does not seriously compromise the performance of these enthalpy exchangers. Theoretical calculations indicate, however, that the transfer of water vapor between airstreams in enthalpy exchangers can significantly diminish their ability to lower indoor formaldehyde concentrations because of the positive coupling between indoor humidity and the emission rates of formaldehyde from building materials.

Keywords: air-to-air, desiccant, energy-conservation, formaldehyde, heat-recovery, mass-transfer, moisture, ventilation.

INTRODUCTION

An increasingly common technique of ventilating residences is to mechanically supply and exhaust approximately equal amounts of air to and from the residence and to transfer heat between the incoming and outgoing airstreams in an air-to-air heat exchanger. The resultant preheating or precooling of the incoming air saves a portion of the energy that is otherwise lost when ventilation occurs without heat recovery. This technique of ventilation with heat recovery is also employed in some commercial buildings.

Some heat exchangers used in ventilation systems, often called "enthalpy exchangers", are designed so that water vapor as well as heat is transferred between airstreams. In summer, when the outdoor air is humid, the transfer of moisture from the incoming to the outgoing airstream will reduce the latent loads on air-conditioning equipment; in winter, moisture transfer from the outgoing to the incoming airstream can reduce humidifications loads. Moisture transfer is not desirable, however, in buildings with a high indoor humidity during the winter, such as many residences with low air infiltration rates.

A potential problem with the utilization of enthalpy exchangers is that some indoor-generated pollutants may be transferred from the outgoing to the incoming airstream, reducing the ventilation system's effectiveness in controlling the concentration of these indoor pollutants. Transfer of pollutants between airstreams can occur by air leakage even in exchangers that are not designed for moisture transfer; however, in enthalpy exchangers there may be additional mechanisms for pollutant transfer. Significant transfer would appear most likely for pollutants that are chemically similar to water or are soluble in water.

Formaldehyde HCHO is a common indoor pollutant in residences and is highly soluble in water. Manufacturer's product literature and results from a previous field study (Offermann et al., 1982) suggest that significant transfer of (HCHO) may possibly occur in some enthalpy exchangers. The product literature supplied by a major manufacturer of enthalpy exchangers (with cores fabricated from a permeable, treated paper) indicates a 21 to 33% transfer rate for highly water soluble ammonia and transfer rates less than 10% for smoke, hydrogen sulfide, carbon monoxide, and carbon dioxide. No data are provided for HCHO or some other common indoor pollutants, such as radon and nitrogen dioxide. In a field study, no significant change in indoor HCHO concentration was measured in two houses when ventilation was provided through these enthalpy exchangers, although substantial reductions in radon concentration and increases in air exchange rate were measured. The results of this field study are not conclusive evidence for HCHO transfer, however, because the relationship between air exchange rate, environmental conditions, and indoor HCHO concentration is complex.

In this paper we first provide background information on two types of enthalpy exchangers available for residential use and discuss potential mechanisms for HCHO transfer. We then describe an experimental study to determine transfer rates of HCHO and two tracer gases in these heat exchangers and discuss the experimental results. The impact of moisture transfer in enthalpy exchangers on indoor HCHO concentrations is also examined analytically.

DESCRIPTION OF HEAT EXCHANGERS AND POTENTIAL TRANSFER MECHANISMS

Heat Exchanger No. 1

A common enthalpy exchanger uses a cross-flow core fabricated from a treated paper. The treatment is described by Tanaka et al. (1982) as impregnation with a "hydrophillic resin and a hygroscopic agent". The core, depicted in figure 1, consists of a series of parallel plates of treated paper with the spaces between adjacent plates subdivided into small triangular passages by paper spacers. The passages are small enough so that the air flow is laminar. The heat exchanger used for the experiments, denoted as "Heat Exchanger No. 1", consists of a core mounted in a sheet metal housing and sealed to the housing to minimize air leakage. The core is used commercially in a residential heat exchanger that is designed for installation without ductwork, i.e., through a wall or window. Product literature for this heat exchanger indicates a sensible heat exchange (temperature) efficiency of approximately 70%. The efficiency of moisture transfer is not given for this particular model; for several other models with a core of the same design but a different size, the reported moisture transfer efficiency is about 10% less than the temperature efficiency.

In this heat exchanger, water vapor, some pollutants, such as ammonia, and heat are transferred directly through the treated paper. The mechanism or mechanisms of gas transfer through the paper are not specified by the manufacturer. From theoretical considerations, the transfer process can be divided into two stages. First, gas molecules must be transferred to the surface of the paper by molecular diffusion through the laminar airstream. This transfer rate is approximately proportional to the diffusion coefficient for the gas through air. The second stage, transfer through the treated paper, may be due to more than one mechanism (Treybal, 1980). If the paper is porous, and the diameter of the pores is greater than about twenty times the mean free path of the diffusing molecule, then ordinary molecular diffusion occurs at a rate that is proportional to the diffusion coefficient for the gas in air. If the pore diameters are less than about 0.2 times the mean free path, then the rate of diffusion through the paper is not controlled by the diffusion coefficient in air, but instead by collisions with the walls of the pores. This process of diffusion, called "Knudsen diffusion", is inversely proportional to the square root of the molecular weight of the diffusing gas. Because the size, shape, and number of pores are generally not known, diffusion rates through porous solids are generally determined experimentally and characterized by an effective diffusion coefficient which is based on the area of the solid, in contrast to the area of the pores.

Some relevant physical characteristics of a diffusing molecule are its size, weight, and diffusion coefficient in air; these are listed in table 1 for water vapor, ammonia (NH_3), HCHO, and the two tracer gases employed in this study -- sulfur hexafluoride (SF_6) and propane (C_3H_8). The molecular size and diffusion coefficient of HCHO do not differ greatly from those of water or ammonia which are known to be transferred through the treated paper at a substantial rate. The molecular size of the SF_6 tracer is considerably greater than the size of the other molecules and the diffusion coefficient of SF_6 in air is also much smaller than the diffusion coefficient of the other molecules.

While untreated paper is a porous solid, the porosity of the paper heat-transfer surfaces in Heat Exchanger No. 1 has been reduced by its treatment (Tanaka et al., 1982), reducing the potential for diffusion through pores. There exists, however, another mechanism (Treybal, 1980) for transport through polymers such as cellulose -- the primary constituent of paper. In this process, the diffusing gas dissolves in the face of the solid and is then transferred through the polymer by a process called "activated diffusion" which involves "jumping" of the diffusing molecules from one position to another within the polymer in the direction of decreasing concentration. The rate of transfer through the polymer is proportional to the product of the solubility of the gas in the solid and the diffusion coefficient for the gas in the solid; this product is given the name "permeability". If the solid is coated with a thin layer of another material, the permeability will depend on the solubility of gas in the coating. The diffusion rate through the solid depends on the size and shape of the diffusing molecules and, in activated diffusion, increases exponentially with temperature. In some oxygenated polymers such as cellulose, molecules that can hydrogen bond to the polymer, e.g., molecules of water or NH_3, diffuse by transfer from one hydrogen bonding site to an adjacent site (Treybal, 1980). It is expected that HCHO could also hydrogen bond to cellulose but it is not known if this hydrogen bonding would occur in a manner that facilitates the transport of HCHO through the cellulose. Another factor that could cause HCHO to be transferred at a lesser rate than water or ammonia is a smaller solubility for HCHO in the unspecified hydrophyllic or hygroscopic materials at the surface of the paper.

A physical characteristic of molecules that may affect their rate of activated diffusion through a polymer such as cellulose is the dipole moment, a measure of electrical polarity. This parameter is listed along with the other molecular characteristics in table 1. Note that the two tracer gases are essentially non-polar and that HCHO, water, and NH_3 are highly polar.

Heat Exchanger No. 2

The second heat exchanger studied experimentally (Heat Exchanger No. 2) transfers heat and moisture by a very different process. The core of the heat exchanger, shown schematically in Figure 2, is a cylindrical wheel constructed from a blend of natural and synthetic fibers and coated with lithium chloride - a common desiccant. The two airstreams pass through the core in counterflow, i.e., opposite directions. The core rotates slowly so that portions previously in contact with the outgoing airstream become exposed to the incoming airstream. Sensible heat is transferred to the core from the warm airstream, stored in the core, and then given up to the colder airstream. Similarly, water vapor from the humid airstream is absorbed by the lithium chloride and later desorbed to the less humid airstream. If a pollutant such as formaldehyde is substantially absorbed by the desiccant, it could also be transferred between airstreams. In addition, if water vapor condenses on the surface of the core or within the lithium chloride coating, water soluble pollutants such as HCHO could dissolve in the condensed water and later be released in the incoming airstream by outgasing of the dissolved pollutant from the liquid water or evaporation of the water. A small amount of transfer, called carryover, also occurs between airstreams (approximately 3% in Heat Exchanger No. 2) because of the wheel´s rotation, and, as in other air-to-air heat exchangers, significant transfer is possible due to air leakage between airstreams.

For the experiments with Heat Exchanger No. 2, we removed the heat-wheel core from a commercially available residential heat exchanger and installed it in a sheet metal case. To minimize leakage between airstreams, we installed an improved set of seals, compared to those in the original heat exchanger. The manufacturer´s product literature indicates that both the temperature and moisture transfer efficiency of the original heat exchanger are 82% at the low fan speed setting and 75% at the high fan speed setting.

EXPERIMENTAL SYSTEM

The experimental system can be subdivided into three subsystems based on the following functions: (1) control and measurement of airstream flow rate, pressure, temperature, and humidity; (2) injection of tracer gases and measurement of tracer gas concentrations; and (3) injection of formaldehyde and measurement of its concentration. In the following discussion of the experimental system, we refer to the "supply" and "exhaust" airstreams. The supply airstream corresponds to the airstream that is drawn from outdoors and delivered indoors after passing through the heat exchanger. The exhaust airstream corresponds to the stream of air that originates indoors, passes through the heat exchanger, and is exhausted to outdoors.

Environmental Control and Measurement

Tests were conducted that simulated operation during both summer and winter. This simulation involved controlling the temperature and humidity of the airstreams that entered the heat exchanger. (The inlet humidity of the supply airstream was not controlled during "winter" tests, but this humidity was typical of the humidity of outdoor air with the same temperature.) The temperature, humidity, static pressure, and flow rate of each airstream were measured upstream and downstream of the heat exchanger as shown in figure 3. A set of air mixing vanes was installed in the ductwork upstream of the locations where air temperature and humidity were measured and where air samples were drawn. A microcomputer logged signals from thermistor-based air temperature probes, relative humidity probes (exhaust airstream only), a hygrometer that draws a small sample of air past a chilled mirror to determine the dewpoint temperature, an electrical pressure tranducer that sensed static air pressure, and a pressure transducer that sensed the pressure drop across the orifice-plate air flowmeters.

Tracer Injection and Measurement

For comparison to the formaldehyde and water vapor transfer rates, we determined the transfer rates of two tracer gases with different molecular weights and diffusion coefficients -- propane (C_3H_8) and sulfur hexafluoride (SF_6). The tracer gases were injected into the exhaust airstream, upstream of the heat exchanger. To ensure mixing of the tracers with the air, they were injected through a manifold upstream of both the orifice plate system and the mixing vanes. Measurement of the tracer gas injection rates, the tracer gas concentrations in the supply airstream downstream of the heat exchanger, and the background tracer gas concentrations (see figure 3) allowed calculation of the transfer rates.

Tracer gas concentrations were measured with infrared analyzers. A microprocessor controlled the operation of a solenoid valve system so that air samples were directed into the analyzers from the airstreams and from cylinders of zero gas and three primary standard calibration gases for each tracer.

Formaldehyde Production and Measurement

Gaseous HCHO was produced by evaporation of a methanol-free aqueous HCHO solution in approximately 20 L/m of air (Pedersen and Fisk, 1984). The resulting HCHO concentration was sufficiently high, 20 to 80 ug/L, for real-time measurement with an infrared analyzer. This concentrated mixture of HCHO in air was then injected into the exhaust airstream in the same manner and location as the tracer gases.

Duplicate measurements were made of the HCHO concentration in each airstream, both upstream and downstream of the heat exchanger. HCHO samples were taken by drawing air through 10 ml of water contained in each of two glass impingers placed in series and immersed in a 7 °C water bath. The rate of airflow through each impinger, approximately 1 L/m, was maintained constant with a flow control system and measured before and after each experiment with a wet test meter. Calculation of HCHO concentrations were based on the flow rates of air through the impingers, the HCHO collection efficiency of the impingers, and the amount of HCHO collected in the impingers, as determined by the modified pararosaniline technique (Miksch et al., 1981). The impingers were calibrated using a dry-formaldehyde generation system (Geisling et al., 1982).

RESULTS

Data Analysis

The transfer fractions of HCHO, C_3H_8, and SF_6 were calculated from the equation:

$$\eta_i = (\dot{M}_{2,i} - \dot{M}_{1,i}) / \dot{M}_{3,i} \qquad (1)$$

where η_i is the transfer fraction of gas i and $M_{1,i}$ through $M_{3,i}$ are the mass flow rates of gas i in airstream 1 (supply inlet), 2 (supply outlet), and 3 (exhaust inlet). The mass flow rates were calculated by taking the product of the gas concentrations and the air flow rates.

A slightly different calculation was employed to determine the mass transfer rate of water vapor, because a significant amount of water vapor was present in the "outside" air (supply inlet airstream). A water transfer effectiveness, ε, defined as the ratio of the water actually transferred to the maximum possible water transfer, was calculated for both the supply (subscript s) and exhaust (subscript e) airstreams using the equations

$$\varepsilon_s = \frac{|W_1 - W_2|}{|W_1 - W_3|} \text{ and } \varepsilon_e = \frac{|W_3 - W_4|}{|W_1 - W_3|} \qquad (2,\ 3)$$

where W is the humidity ratio of an airstream, subscripts 1 through 3 were defined for equation 1, and subscript 4 denotes the exhaust outlet airstream (see figure 3). Note that for the calculations of water transfer effectiveness, the humidity ratios rather than the water vapor mass flow rates were used; the flow rates of the supply and exhaust airstreams were nearly equal and the small resultant correction to the water transfer effectiveness was not justified considering the uncertainties in measurement of humidity ratio. If the airstream flow rates were identical, then the two water transfer effectiveness should also be identical.

Mass balance ratios for HCHO, water, and dry air were calculated from the equation:

$$R_i = (\dot{M}_{2,i} + \dot{M}_{4,i}) / (\dot{M}_{1,i} + \dot{M}_{3,i}) \qquad (4)$$

where R_i is the mass balance ratio for gas i. The mass balance ratios are indicators of the accuracy of the air flow rate, humidity, and formaldehyde concentration measurements.

Uncertainty Analysis

The uncertainty of our measurements of HCHO transfer fraction is estimated to be less than 12% of the measured value. This is based on an uncertainty in the air flow rates of 2% and an uncertainty of less than 3% in the determination of a ratio of HCHO concentrations. Our estimate of the uncertainty in the measurement of tracer gas transfer fraction is ± 0.01 or less.

Transfer Rates

The transfer fractions of HCHO, C_3H_8, and SF_6, the water vapor transfer effectiveness, and the mass balance ratios are presented in table 2. This table also lists the temperature and humidity of the two inlet airstreams of the heat exchanger and the formaldehyde concentration in the "indoor" air (exhaust inlet airstream). The flow rates of the inlet airstreams of the heat exchangers were 27 to 30 L/s during tests of Heat Exchanger No. 1 and 20 to 22 L/s during tests of Heat Exchanger No. 2. These flow rates are representative of the manufacturers' design flow rates for each heat exchanger. Supply and exhaust airstream flow rates differed by no more than 6%.

In tests of Heat Exchanger No. 1, the HCHO transfer fractions were 0.068 to 0.12. The transfer fractions were slightly greater, 0.090 to 0.15, in tests of Heat Exchanger No. 2. The HCHO transfer fractions are depicted graphically in figures 4 and 5, for winter and summer tests, respectively. On average, the HCHO transfer fractions were slightly higher during summer tests, perhaps due in part to the higher air temperatures. The average HCHO transfer fractions were also slightly greater during winter tests with a high indoor humidity and summer tests with a high outdoor humidity, compared to the corresponding winter and summer tests conducted at lower humidities. Neither the direction of water transfer nor the concentration of HCHO in the indoor air had a discernable effect on the HCHO transfer fractions.

Another quantity depicted in figures 4 and 5 is the transfer fraction of HCHO less the transfer fraction of SF_6. In a later section, we suggest that the predominant mechanism for SF_6 transfer is leakage of air between airstreams. If leakage is indeed the cause of SF_6 transfer, then the difference between the HCHO and SF_6 transfer fractions is an indicator of the HCHO transfer that occurs by processes other than air leakage, i.e., due to the fact that these exchanges are "enthalpy" exchangers. The transfer fraction of HCHO exceeds that of SF_6 by only 0.01 to 0.09.

Because the HCHO mass balance ratios for tests 1-8 and 1-9 are poor, the uncertainty in the HCHO transfer fraction for these two tests is greater than for other tests. The low mass balance ratio of test 1-9 was probably caused by condensation of water vapor in the HCHO sampling lines and dissolution of HCHO into this water; we are unsure of the cause of the poor HCHO mass balance for test 1-8.

Three tests were repeated, i.e., a second test was conducted with nearly identical inlet conditions, and the HCHO transfer rates measured during these nearly identical pairs (1-12 and 1-14, 2-C and 2-D, and 2-F and 2-G) were also essentially identical.

The C_3H_8 and SF_6 transfer fractions ranged from 0.05 to 0.08 for tests of both heat exchangers. The transfer fractions of the two tracer gases were greater during summer tests than during winter tests. Tracer gas transfer data were not available for a few tests due to equipment failures.

The water transfer effectivenesses of Heat Exchangers No. 1 and No. 2, respectively, were 0.23 to 0.35 and 0.49 to 0.66. These data are not reported for some tests because of failure in the operation of our chilled mirror hygrometer or because there were large differences between ε_s and ε_e. (The small differences between the humidity ratios of the supply and exhaust airstreams made measurement of ε difficult.) From the available data, it was not possible to discern if airstream temperatures or humidities had an effect on water transfer effectiveness. The imprecision of our humidity data and the imperfect water mass balances indicate that there is substantial but unquantified uncertainty in our measurements of water transfer effectiveness.

DISCUSSION

Transfer Mechanisms

In a previous section, we discussed possible mechanisms of gas transfer in each heat exchanger. While the test results are not sufficient for definitive conclusions about transfer mechanisms, the results do provide evidence as to the importance of various mechanisms.

In Heat Exchanger No. 1, the transfer of gases between airstreams occurs by passage directly through the treated paper and by leakage of air between airstreams. Gas transfer through pores in the core material by ordinary diffusion and/or Knudsen diffusion (described previously) does not appear to be the predominant transfer mechanism. The relationship between the transfer rates of the four gases examined (HCHO, C_3H_8, SF_6 and water vapor) do not correspond with predictions based on our understanding of ordinary or Knudsen diffusion. In particular, while the measured transfer fractions of C_3H_8 and SF_6 were nearly identical, the predicted transfer fraction of C_3H_8 by ordinary or Knudsen diffusion through pores is approximately 1.7 times the predicted transfer fraction of SF_6. The discrepancy from theoretical predictions and our previous experience with heat exchangers suggest that the primary transfer mechanism for C_3H_8 and SF_6 is leakage of air between airstreams.

The transfer fractions of both HCHO and water vapor were significantly greater than those for the C_3H_8 or SF_6 tracer gases. These differences cannot be caused by leakage of air or the two diffusion processes mentioned above; therefore, HCHO and water vapor must be transferred at a significant rate by an additional process (or processes).

In Heat Exchanger No. 2, the transfer fractions of C_3H_8 and SF_6 were 0.05 to 0.07. Since carry-over is responsible for a transfer fraction of about 0.03 (for all gases), and since some leakage between airstreams is expected, these two transfer processes are most likely responsible for the bulk of the C_3H_8 and SF_6 transfer. It is clear that there are additional mechanisms for transport of water and HCHO, because they are transferred at a greater rate than the tracer gases. Transfer by absorption on and desorption from the lithium chloride coating of the heat wheel, which is known to be important for water, is also a likely source of HCHO transfer. The measured increase in HCHO transfer with increased airstream humidities indicates that HCHO molecules may possibly attach to water molecules on the heat wheel. The test data did not, however, provide strong evidence for the existence or absence of liquid water on the core or the role of HCHO dissolution in liquid water on HCHO transfer.

Impact on Indoor Formaldehyde Concentrations

The ability of a ventilation system that includes an air-to-air heat exchanger, to remove indoor pollutants is compromised by pollutant transfer within the heat exchanger from the exhaust to the supply airstreams. In the two enthalpy exchangers tested, only a small fraction (.01 to .09) of the HCHO in the exhaust airstream was transferred by processes other than air leakage to the supply airstream. This HCHO transfer will reduce, by a similarly small fraction, the ventilation system's ability to remove HCHO from the indoor space. The transfer of HCHO between airstreams will generally cause the indoor HCHO concentration to increase by a smaller fraction than the HCHO transfer because: (1) only a portion of the building's ventilation is normally supplied through the enthalpy exchanger, and (2) the emission rate of HCHO from many source materials is often dependent (Matthews, et al., 1983) on the indoor HCHO concentration.

Another aspect of the performance of enthalpy exchangers -- the transfer of water vapor between airstreams -- can, however, have a significant impact on indoor HCHO concentrations. When the outdoor air has a lower humidity ratio than the indoor air, ventilation provided through an enthalpy exchanger will not reduce the indoor humidity as greatly as ventilation that occurs without moisture transfer. Because the rate of formaldehyde emission from typical indoor formaldehyde sources (such as pressed-wood products and urea-formaldehyde foam insulation) increases with an increase in the indoor humidity, ventilation through an enthalpy exchanger will not reduce indoor formaldehyde levels as substantially as ventilation without water vapor transfer.

To estimate this impact of water vapor transfer on indoor formaldehyde concentrations, we employed a simple water mass balance model for a residence and data relating indoor humidity to formaldehyde concentrations. Calculations were performed for a residence with an interior volume of 340 m^3, 0.25 air changes per hour (ACH) of natural ventilation, and 0.5 ACH of mechanical ventilation through an enthalpy exchanger. The calculations indicate that a change in the water vapor transfer effectiveness of the heat exchanger from 0.1 (representing a typical rate of water vapor transfer due to leakage) to 0.3, will cause the indoor relative humidity to increase by 2 to 3 percentage points (at 20 ^{o}C) assuming indoor water vapor source strengths of 0.5 to 1.0 kg/h. For a change in water vapor transfer effectiveness from 0.1 to 0.6, the indoor relative humidity will increase by 6 to 14 percentage points for the same range of water vapor source strengths. Available data generally show that a 10 percentage point increase in indoor relative humidity will cause approximately a 20% increase in indoor HCHO concentrations (Andersen, Lundquist, and Molhave, 1975; Berge, et al., 1980). Therefore, the 2 to 14 percentage point increase in relative humidity noted above would cause a 4 to 28% increase indoor HCHO concentration.

Another type of enthalpy exchanger that can transfer water vapor and HCHO between airstreams is an exchanger with a heat wheel core that is not coated with a desiccant. Under certain indoor and outdoor environmental conditions, water vapor will condense out of the exhaust airstream onto the surfaces of the heat wheel. This water vapor may then evaporate into the supply airstream and return to the indoor space. Since HCHO is highly soluble in water, it is likely that some HCHO will be transferred with the water and also be returned to the indoor space. The extent of HCHO and water vapor transfer in this type of heat exchanger has not been determined. However, based on simple calculations we expect that in most U.S. climates, substantial HCHO and water vapor transfer is likely to occur only during a small fraction of the heat exchanger's operating time.

CONCLUSION

The major definitive conclusion of this work is that transfer of formaldehyde between airstreams, by processes other than air leakage, is not a major problem in the two enthalpy exchangers examined. The transfer of water vapor between airstreams in enthalpy exchangers will, however, lead to higher indoor humidities and, thus, higher formaldehyde emission rates when the outdoor humidity ratio is lower than the indoor humidity ratio. For a hypothetical building, theoretical calculations indicate a 4 to 28% higher indoor HCHO concentration when the mechanical ventilation is provided through an enthalpy exchanger in contrast to a heat exchanger that is not designed to transfer moisture between airstreams.

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Table 1
Comparison of Physical and Chemical Properties

Gas	H_2O	HCHO	NH_3	C_3H_8	SF_6
Molecular Weight	18.01	30.03	17.03	44.11	146.05
Approx. Molecular Diameter (Å)	2.60*	3.70+	2.90*	5.10*	7.80#
Diffusivity in air - reported (cm^2/S)	0.26*	0.00	0.23*	0.00	0.00
Diffusivity in air - calculated (cm^2/S)	0.22*	0.19*	0.23*	0.12*	0.07*
Dipole Moment (D)	1.85**	2.33**	1.47**	0.08**	0.00**

* Treybal, 1980
\+ Estimated from data on bond lengths and atomic diameters.
\# Masterton and Slowinski, 1973.
** Weast, 1977.

Table 2
Results of Formaldehyde and Tracer Gas Transfer Tests.

										Environmental Conditions[6]							
		Transfer Fractions[3]			Water Transfer Effectiveness[4]		Mass Balance Ratios[5]			Supply Inlet			Exhaust Inlet			
Test No.	Test Category	η_{HCHO}	$\eta_{C_3H_8}$	η_{SF_6}	ε_s	ε_e	R_{HCHO}	R_{water}	R_{air}	T_1(°C)	W_1	RH_1	T_3(°C)	W_3	RH_3	$[HCHO]_3^7$
1-6	W - L	0.079	0.06	0.05	0.00	0.00	0.94	0.98 - 1.04	1.02	4.6	38	73	20.9	48	31	452
1-7	W - L	0.086	N.A.	0.05	-	-	0.97	1.00 - 1.04	1.02	4.6	38	71	20.9	47	30	187
1-16	W - L	0.068	0.07	0.06	0.23	0.25	0.95	0.98 - 1.05	1.02	4.9	40	75	21.2	66	41	462
1-5	W - H	0.10	0.06	0.05	0.29	0.35	0.99	0.94 - 1.06	1.02	4.8	39	75	23.5	87	48	991
1-8	W - H	0.099	N.A.	0.05	0.35	0.31	0.83	1.00 - 1.06	1.02	4.6	39	73	20.9	75	48	991
1-15	W - H	0.12	0.07	0.06	-	-	1.00	N.A.	1.03	4.8	50	95	20.7	91	60	276
1-11	S - L	0.10	0.08	N.A.	-	-	0.98	N.A.	1.02	32.2	55	18	24.9	104	53	439
1-9	S - H	0.12	N.A.	N.A.	-	-	0.84	N.A.	1.01	31.8	130	44	20.9	95	61	369
1-12	S - H	0.12	0.08	0.08	-	-	0.97	0.86 - 1.00	1.01	32.5	187	59	24.9	95	47	416
1-13	S - H	0.12	0.08	0.07	0.23	0.24	0.98	0.94 - 1.10	1.01	31.8	149	49	24.8	93	46	231
1-14	S - H	0.12	0.08	0.07	0.28	0.26	0.95	0.98 - 1.04	1.01	32.0	170	55	24.8	88	45	477
2-B	W - L	0.093	0.06	0.06	0.54	0.49	0.96	1.01 - 1.04	1.02	5.9	38	66	21.3	47	29	318
2-C	W - L	0.090	0.06	0.06	0.51	0.55	0.98	1.00 - 1.04	1.02	6.2	38	64	21.2	43	27	411
2-D	W - L	0.092	0.06	0.06	-	-	0.98	0.99 - 1.03	1.02	6.4	38	64	21.2	37	23	406
2-A	W - H	0.13	0.05	0.06	0.64	0.65	0.98	1.00 - 1.03	1.02	6.0	38	65	21.2	77	48	366
2-E	S - L	0.090	0.07	0.06	0.66	0.60	0.96	1.00 - 1.04	1.01	32.2	64	20	24.9	92	46	558
2-F	S - H	0.15	0.07	0.07	-	-	0.98	1.1 - 1.3	1.01	32.1	168	54	24.9	100	50	442
2-G	S - H	0.15	0.06	0.06	-	-	1.00	N.A.	1.02	32.1	193	62	25.0	107	53	499

1. "1 - " and "2 - " denote tests of heat exchangers No. 1 and No. 2, respectively.

2. "W - L" and "W - H" indicate winter condition tests with low and high supply inlet airstream humidities, respectively.
"S - L" and "S - H" indicate summer condition tests with low and high exhaust inlet airstream humidities, respectively.
Other environmental conditions for each test category were typically the same.

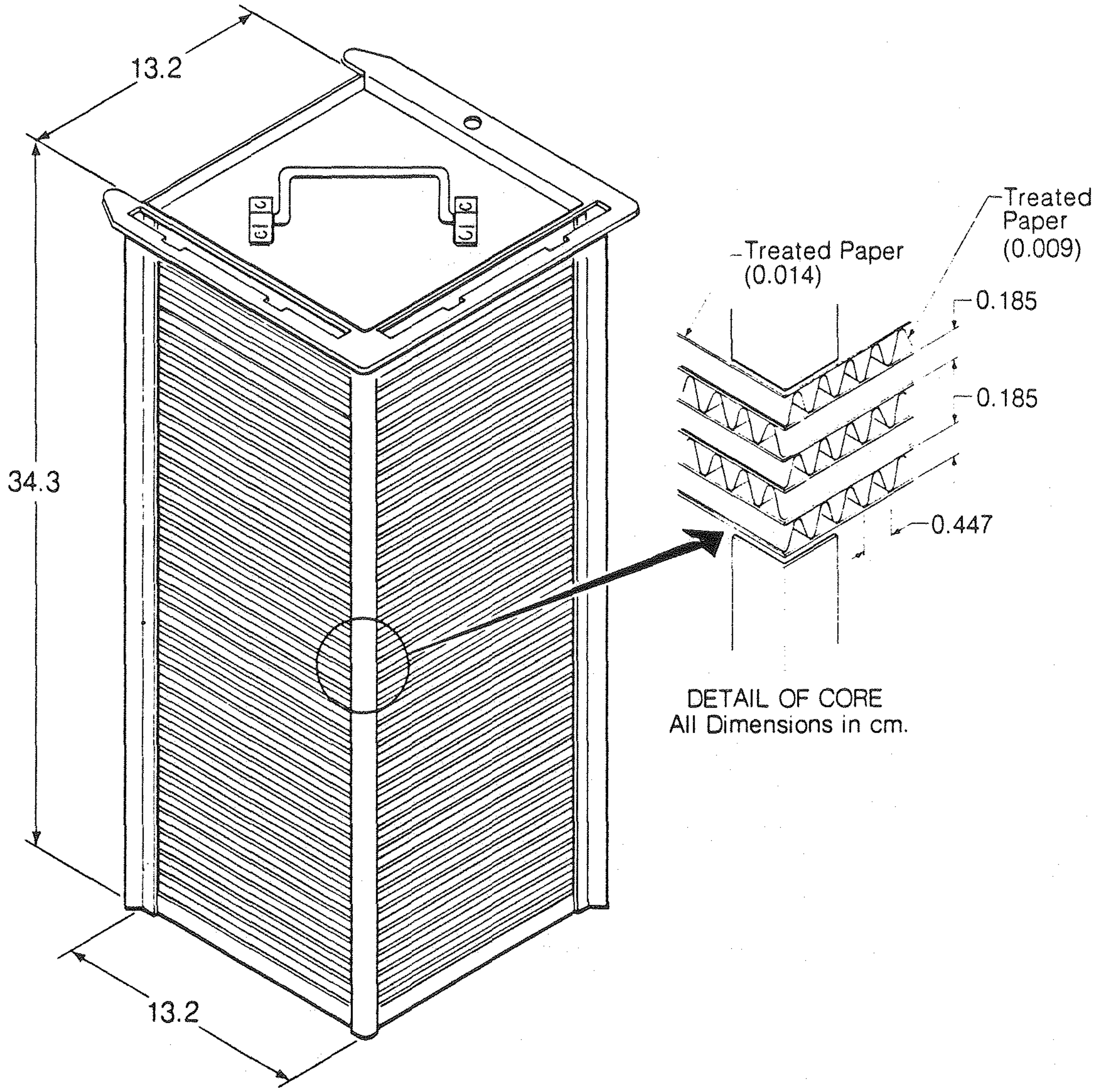
3. HCHO = Formaldehyde; C_3H_8 = Propane; SF_6 = Sulfur Hexaflouride. N.A. = Not Available due to equipment failure.

4. Subscripts s and e denote supply and exhaust airstreams, respectively. Data is not presented for all tests; see text.

5. A range of R_{water} are presented since there were variations during the tests. N.A. = Not available due to equipment failure.

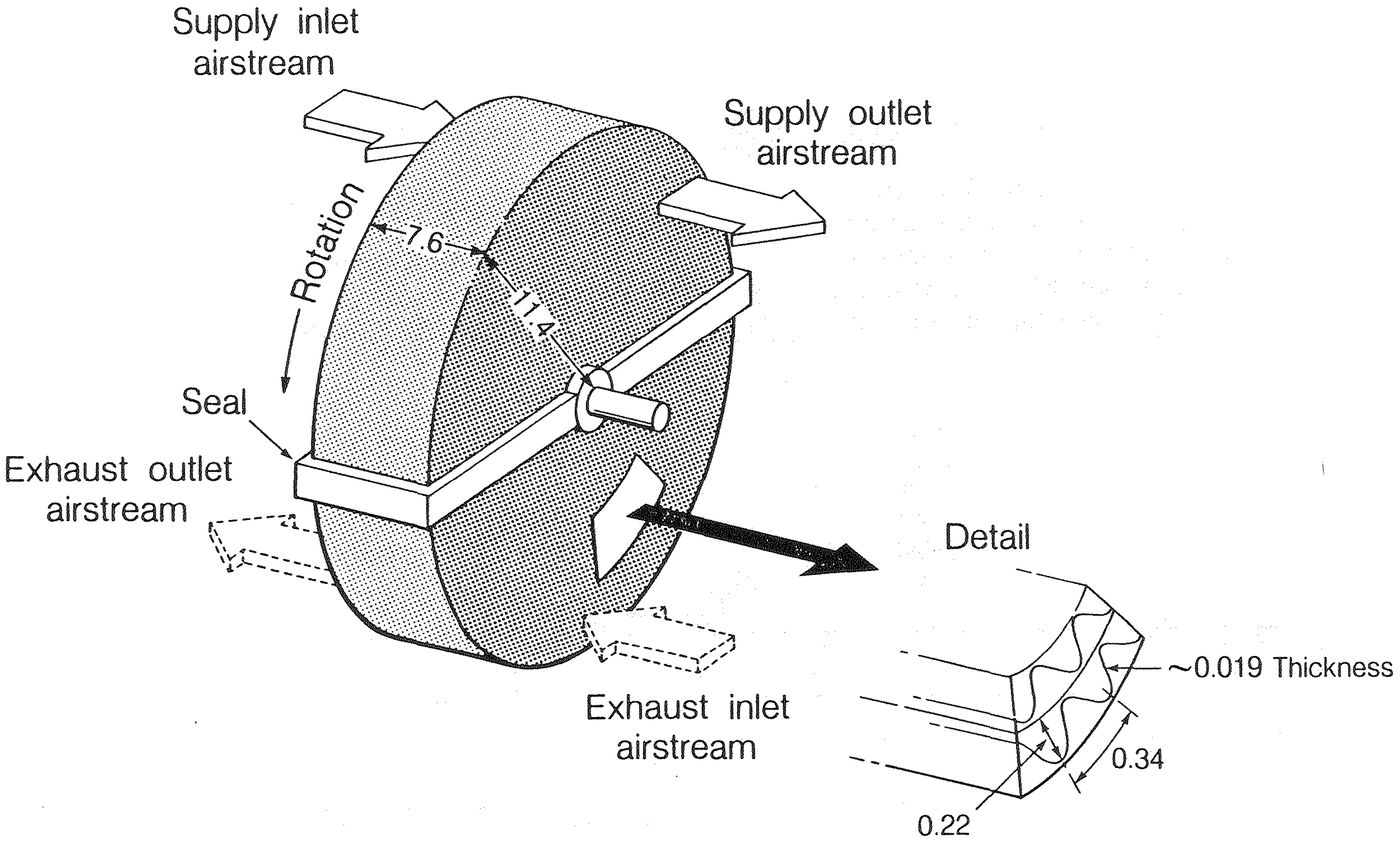
6. T = Temperature; W = Humidity Ratio x 10^6; RH = % Relative Humidity.

7. $[HCHO]_3$ = Formaldehyde concentration (ng/L at 25 °C) in exhaust inlet airstream.



XBL 8310-12238

Figure 1. Illustration of core of Heat Exchanger No. 1. This design is protected by patents.



All dimensions are approximate in cm.

XBL 847-9832

Figure 2. Illustration of core of Heat Exchanger No. 2. The seal around the circumference of the heat wheel is not shown. This design is protected by patents.

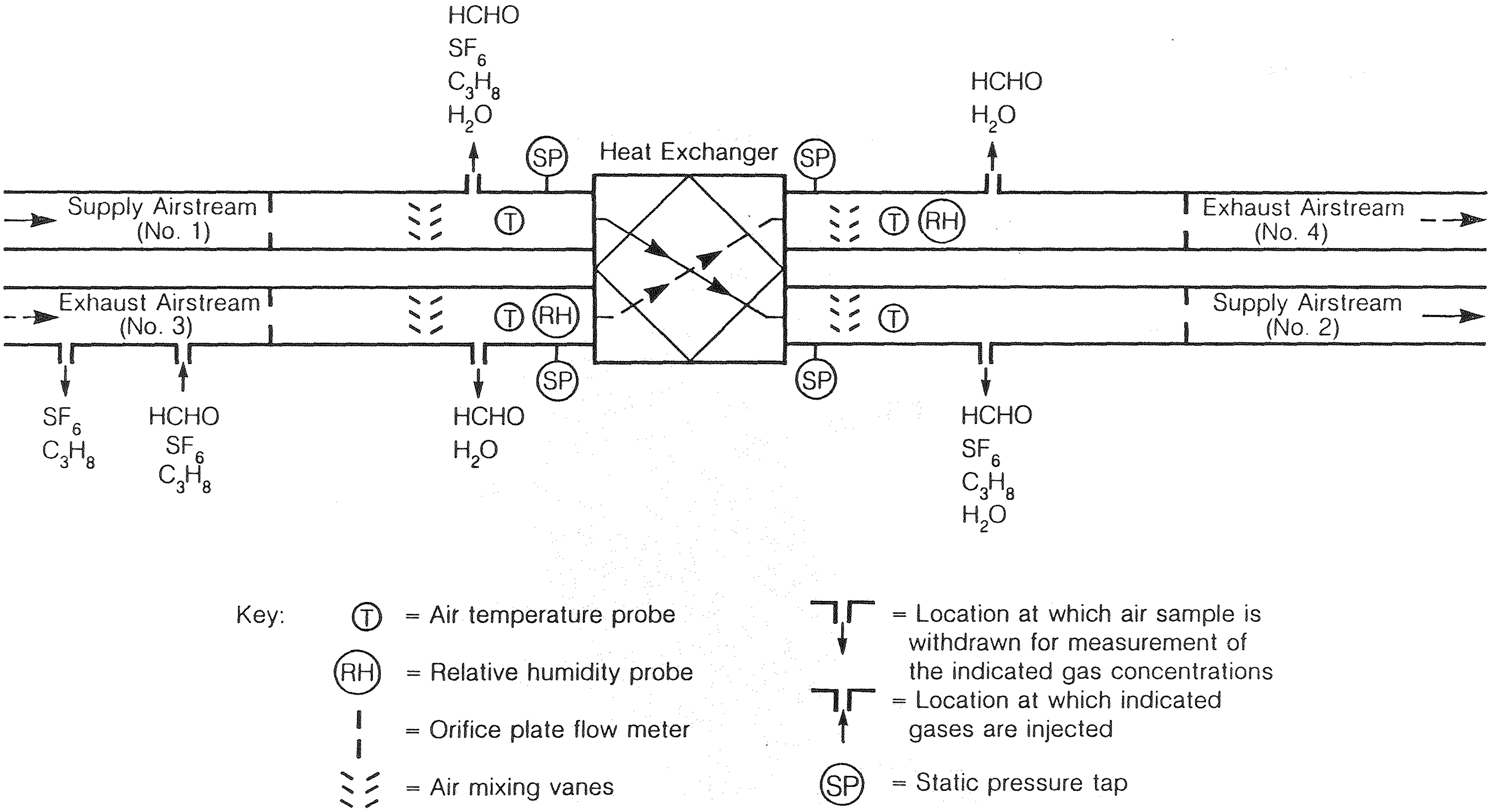
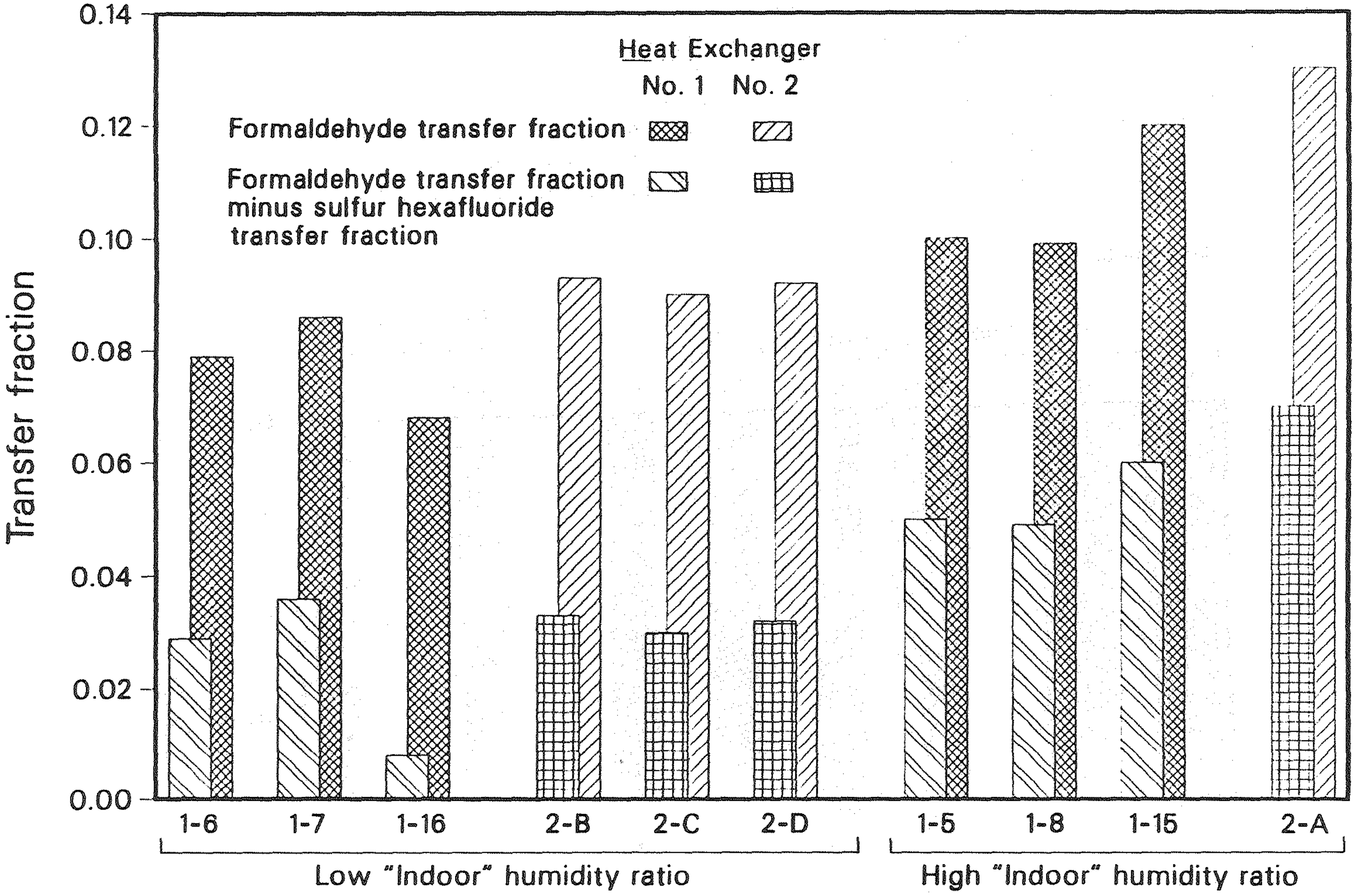
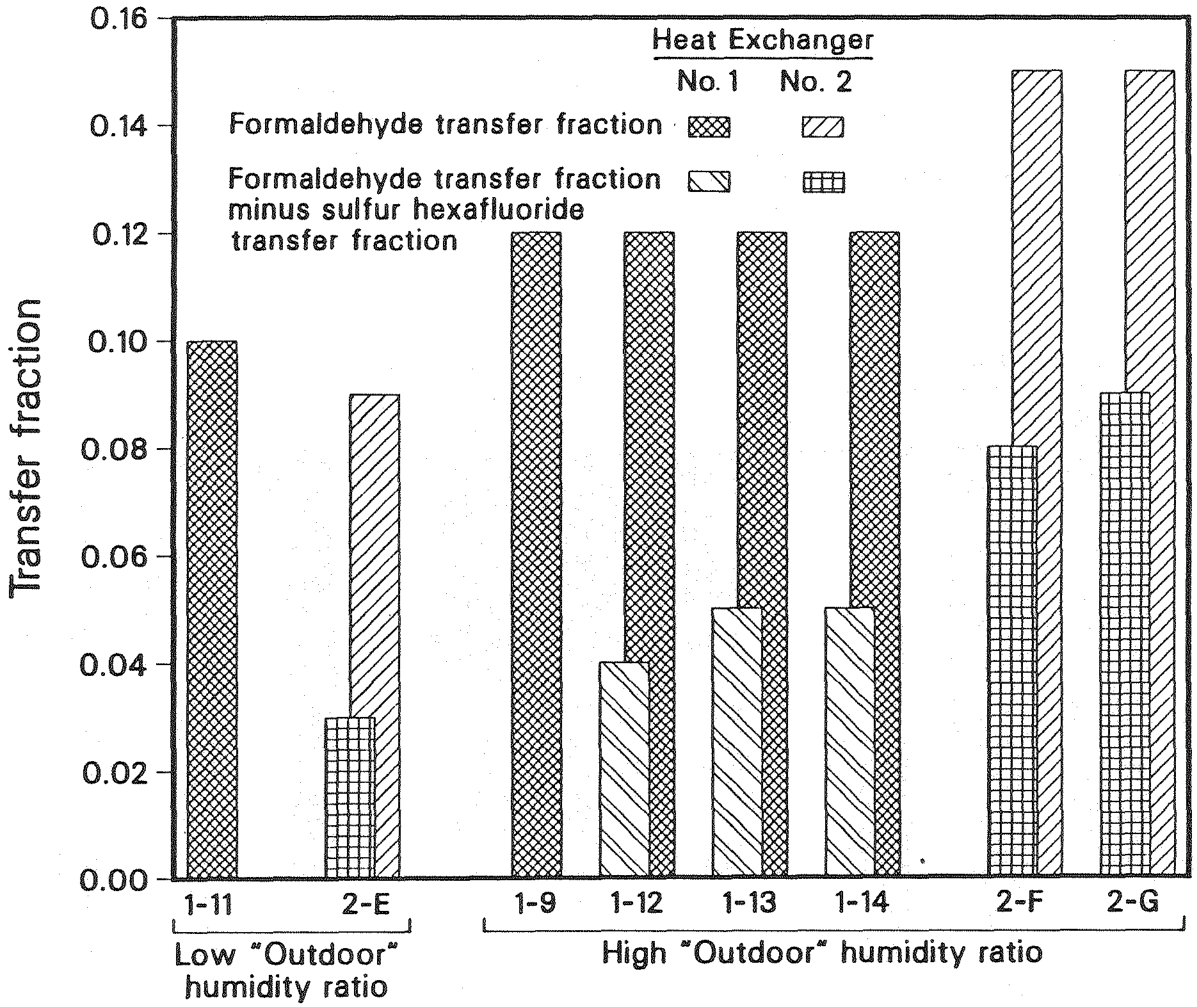


Figure 3. Schematic diagram of experimental system showing locations of formaldehyde and tracer gas injection, air sampling, and airstream property measurements.



XCG 847-13166

Figure 4. Formaldehyde transfer fractions measured during "winter" tests. The results are grouped into tests where the indoor humidity ratio was low (0.0037-0.0066) and high (0.0075-0.0091). The estimated uncertainty in the formaldehyde transfer fraction is less than 12% of the measured value. Also shown is the difference between the formaldehyde and sulfur hexaflouride transfer fraction. Test numbers are listed below the bars: "1-" and "2-" denote tests of Heat Exchangers No. 1 and No. 2, respectively.



XCG 847-13167

Figure 5. Formaldehyde transfer fraction measured during "summer" tests. The results are grouped into tests where the outdoor humidity ratio was low (0.0055-0.0064) and high (0.0130-0.0193). The estimated uncertainty in the formaldehyde transfer fraction is less the 12% of the measured value. Also shown is the difference between the formaldehyde and sulfur hexaflouride transfer fractions (this difference is not available for two tests due to equipment failures). Test numbers are listed below the bars: "1-" and "2-" denote tests of Heat Exchangers No. 1 and No. 2, respectively.