THE VARIATION OF INFILTRATION RATE WITH RELATIVE HUMIDITY IN A FRAME BUILDING

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INTRODUCTION

During a period of several years, Honeywell has been studying residential heating and cooling systems in great detail. The measurement of infiltration rates is an important part of this program. Humidification is also of major interest in this systems project. During the course of the work an unexpected correlation between infiltration and inside relative humidity emerged. After this was noticed, some tests for the next year were designed to study this specific hypothesis. Therefore, the two-year study was not as rigorous as one designed for the purpose at the outset. The observed results are being offered here because they indicate a significant energy saving benefit from increasing relative humidity above the normally low winter indoor RH. This is an important consideration in the general subject of humidification especially with the need for energy conservation.

It is the authors' hope that others will perform corroborating experiments in the future.

TEST RESIDENCE AND INSTRUMENTATION

Details of the house and surroundings used in the infiltration study are shown in Figures 1, 2, and 3. The quality of workmanship in the house is considered good. It is heated by a forced-air-natural-gas-fired heating unit of 80,000 Btu/hour (23,400 Watt) capacity. Cooling is provided by an air-cooled remote air conditioning unit.

The house is located 1.5 miles (2,400m) west of the official weather station at the Minneapolis-Saint Paul International airport. The closer half of that distance is filled with a typical suburban development of single story houses and immature trees. The remainder of the distance is airport buffer zone.

The house was equipped with a weather station to permit determination of exact local conditions which are used in this report. Weather records from the official weather station were also obtained for reference. An aneomometer and weather vane measured wind speed and direction. Temperature was determined by a resistance bulb in a ventilated white enclosure mounted on a post extending above the roof of the house. Outdoor relative humidity was obtained from the official weather station. Indoor relative humidity was measured using a laboratory resistance-type sensor.

When possible, weather data measured at the house was used for the study. During the first experiments (before the house weather station was in operation) only official weather bureau data was available. Subsequent experimental data provided matching pairs of official and local weather. A correlation of wind speed, direction, and air temperature was computed and used to estimate local weather conditions for the first experiments. A good correlation was obtained with temperature but wind speed and direction were apparently modulated in a complex fashion by surrounding trees and buildings resulting in only fair correlation.

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Helium is commonly used as a tracer gas in infiltration studies.(1) A "residual infiltration", in excess of the actual, under no wind or temperature stress is found when helium is used,(2,3) caused by the mobility of helium combined with the concentration gradients during the studies. Gases with greater molecular weight generally produce lower "residual infiltration". Chlorothene (Dow Chemical's 1,1,1-trichlorethane) was chosen as the tracer gas for these studies because it is readily measured (4) by an inexpensive continuous instrumental method and is less toxic than other chlorinated solvents of similar molecular weight. Its molecular weight is 133 compared to air at 29 and helium at 4. An undesirable side effect from using Chlorothene is corrosion of the hot heat exchanger surfaces.

TEST PROCEDURES AND RESULTS

The infiltration rate (air changes/hour) was determined by observing the decrease rate of Chlorothene concentration in the house. During the studies the furnace fan was on continuously and the heat was on the normal demand cycle governed by the thermostat. The house was unoccupied but under otherwise normal conditions. Up to February 26, the house was also unfurnished. Before each test Chlorothene was sprayed on the furnace filter in the return-air duct, as shown in Figure 4. Spraying was stopped when the desired concentration (up to 400 parts per million) was reached, and a half-hour equilibration time allowed before the test was begun. The normal air flow from the furnace fan mixed the Chlorothene and air.

The Chlorothene concentration was measured with a Davis Halide Meter located near the center of the main floor in the kitchen. This meter is shown in Figure 5. Samples were drawn from six locations by a manifold. Sampling tubes were approximately 6 inches (15 cm.) from the floor in the center of the kitchen, living room, and each bedroom. Another tube was near the center of the unfinished ceiling in the basement and a sixth in the vertical section of the furnace return duct, positioned horizontally about 6 feet (2 m) above the floor. This duct tube was of perforated brass to average conditions in the duct. Earlier experiments with an open tube revealed variations in Chlorothene concentrations across the duct.

A complete set of data was collected from the six sampling points in 5 minutes. After allowing 50 seconds for purging the tube and equilibration, that reading was taken and process continued for all six tubes.

Data was collected sequentially for at least one (1) hour after passing the 300 ppm (parts per million) Chlorothene concentration level. Data from each location was graphed semilogarithmically with time to determine the infiltration rate for each area. The formula, (5)

$$I = \left[\frac{1}{t_2 - t_1}\right] \ln \left[\frac{C_1}{C_2}\right] \text{ was used,}$$

where

I = infiltration rate, air changes per hour

t = time in hours

C = Chlorothene concentration, ppm

where $t_2 - t_1 = 1$ hour, $C_1 = 300$ ppm at t_1 (arbitrary starting point), and C_2 is the concentration of Chlorothene one hour after 300 ppm. The equation reduces to;

$$I = \ln \frac{300}{C_2}$$

All infiltration rates were calculated from the curves in the same manner. In each of the experiments infiltration rates for all sampling locations were identical within 5%. The average infiltration values were used and are recorded in the Table of Data. Early experiments were performed without indoor relative humidity data but their values could be estimated from data obtained in later experiments based upon humidifier operation and recent history of outdoor temperature and humidity. Time (date) was found to be an important factor due to the high RH-inertia of the house.

DISCUSSION OF RESULTS

The initial purpose of these experiments was to model the infiltration characteristics of the house for use in other studies. The relationship was expected to have the form

$$I = A + BV^2 + C\left[\frac{1}{T_o} - \frac{1}{T_i}\right]$$

where I is the observed infiltration rate, V is the wind speed, T_o and T_i are the absolute outdoor and indoor temperatures, and A, B, and C are constants. (This is sometimes approximated $I = A + BV + C\Delta T$)

Regression analysis of the data showed a very poor correlation but a trend indicating the physical properties of the house were changing resulting in changes in the constants A, B, and C. The principle influence appeared to be time or the chronological order in which the experiments were run. Later it became evident that the time dependent variable was the moisture content of the wood. The absolute humidity in the house was affected by weather conditions and humidifier operation.

After this hypothesis was made, starting with the experiment of February 20, 1963, indoor RH measurements were made. In those experiments for which indoor RH data was not available a logical time - based RH shift was assumed. In all cases the RH was converted to absolute humidity expressed as partial pressure of water vapor in mm of mercury units.

The term "base infiltration rate" is defined as the infiltration which results from diffusion after wind speed and temperature difference are reduced to zero. This term which represents the leakiness of the house also acts as a multiplier on the constants B and C

$$I = I_o \left(A + BV^2 + C\left[\frac{1}{T_o} - \frac{1}{T_i}\right]\right)$$

where I_o is the base infiltration rate.

The constants A, B, and C were determined from the data obtained from February 23, 1963 to February 26, 1963. The most accurate method of determining these constants is to perform a direct regressional analysis on the non-linear relationship. Due to the enormous volume of computation required for this model, a linear approximation was chosen. A linear regression analysis produced approximations for the constants A, B, and C. $I = I_o\left(1 + 0.0354V^2 + 3600\left[\frac{1}{T_o} - \frac{1}{T_i}\right]\right)$ where V is in miles per hour and T is in absolute degrees Fahrenheit ($I = I_o\left(1 + 0.0137V^2 + 2000\left[\frac{1}{T_o} - \frac{1}{T_i}\right]\right)$ where V is in Km/hr. and T is in degrees Kelvin.)

Then the influence of wind and temperature difference were eliminated from the model and the data. The resulting curve relating base infiltration (I_o) to equilibrium wood-water vapor pressure (Pe) is shown in Figure 6.

Figure 7 illustrates the trends of the above data-set during the period of increasing relative humidity and resulting increasing wood-water vapor pressure. Note that after the RH changed, the total and base infiltration rates decrease and approach limiting values and the wood-water vapor pressure approaches its limit.

As stated above, the dimensional changes of the hygroscopic building materials (primarily lumber) could be responsible for the changes in base infiltration rate. Moisture content of these materials under equilibrium conditions is dependent upon ambient absolute humidity. The moisture content, in turn, determines the dimensions of the lumber. The following analysis is made to support this hypothesis.

Free water in lumber, in excess of fiber saturation, may vary from 25 to 300 per cent without significant effect on dimensions. Water bound in wood fibers, however, has a profound effect on dimensions.

When drying from green lumber to the air-dry condition, fir or pine shrinks dimensionally by these percentages (6):

Tangentially (to the growth ring)	2.1 - 7%
Radially	1 - 4.2%
Longitudinally	0.05 - 0.1%

And this amount of shrinkage roughly doubles when lumber reaches the completely dry condition. Note that longitudinal dimension changes are relatively insignificant.

The equilibrium moisture content and shrinkages from the green condition for fir and pine are (7,8):

Relative humidity at 70°F, %	10	20	30	40
Partial pressure, Pe, mm water vapor	1.9	3.8	5.6	7.5
Equilibrium moisture content, %	3	4.5	6	8
Shrinkage, % of green (radial)	4.3	4.1	3.8	3.4
Shrinkage, % of green (tangential)	6	5.7	5.3	4.7

Response time for such shrinkage is affected by the degree of vapor-sealing from paint, varnish, plaster, stucco, or other covering. From the data, a time constant of ten (10) days was calculated.

In shifting from 20 to 40 per cent relative humidity, therefore, the wood's radial dimension increases 0.7 per cent and the tangential dimension as much as one per cent. The longitudinal dimension changes only 0.025 per cent, as calculated by comparing the data from references 6, 7, and 8.

In window construction and mounting the net result of swelling is difficult to analyze. In a simple way, consider the dimensional changes that might occur in a double-hung window unit shown in Figure 8, as the relative humidity increases from 20 to 40 per cent. Longitudinal dimensional increase of wood:

$$30'' \frac{(0.025)}{100} = 0.0075'' \qquad \left(76 \text{ cm} \frac{(0.025)}{100} = 0.019 \text{ cm}\right)$$

This dimensional change in the window unit would be nearly cancelled by a similar change in the window framing lumber. Average radial and tangential dimensional increase, each member is:

$$2'' \frac{(0.85)}{100} = 0.017'' \qquad \left(5 \text{ cm} \frac{(0.85)}{100} = 0.043 \text{ cm}\right)$$

This increase will be bound within the longitudinal dimensions of the frame. The net dimensional increase across the window is:

$$2 \ (0.017'') = 0.034'' \qquad (2 \ (0.043 \text{ cm}) = 0.086 \text{ cm})$$

The crack width around windows is usually assumed to be 0.04" (1) (0.1 cm) for a normal window unit. Therefore, the calculated dimensional increase, applied equally to each side of the window unit, would cut the wondow crack dimension approximately in half, proportionally decreasing the infiltration rate around this window. Weatherstripping complicates this analysis.

The wall sections in which the windows are mounted would also be expected to swell. This added swelling is predicted to be small since the wall framing lumber is protected by reasonably good vapor barriers. The effects of outdoor RH versus indoor RH and outdoor temperature versus indoor temperature on the cross-sectional wood moisture gradient are not included in this analysis. However, the same principles of decreased infiltration at high outdoor RH would apply to the outer members of window frames and storm windows. Therefore, variations in outdoor RH are expected to have an effect on infiltration also.

The values used for humidity variations and crack widths in the example are considered typical for this study. Comparison of measured infiltration data before and after humidification gives results similar to those predicted by the analytical treatment.

It should also be noted that the effect of humidity will be proportionately more pronounced for the tighter window and door structures. If a residence is very poorly fitted and weatherstripped the percentage change in crack width due to this effect is expected to be much less.

CONCLUSIONS

The study indicates that increasing the inside relative humidity can significantly reduce infiltration of outside air during the heating season, thereby reducing heating requirements and costs. The heat loss from infiltration was reduced by up to 50 per cent in these experiments. In a typical house, infiltration can represent approximately one-fourth the total heat loss. Applying a tolerance to these estimates, this means that increasing the RH from 20 to 40% is predicted to save from 5 to 15 per cent on fuel costs during an average heating season. The energy penalty to evaporate humidification water is not considered in this analysis due to the variability in water requirements and the multitude of sources of this water: humidifier, cooking, washing, etc.

As additional benefits of humidification, damage to furniture, books, clothing, and leather goods caused by dryness can be reduced. Also, personal discomfort due to static electricity, dry hair, skin and respiratory passages can be reduced.

ASHRAE(9) reports indicate that raising the relative humidity permits a slightly lower air temperature and thus a slight savings in heat requirements. More importantly, a comfort benefit with increased inside relative humidity should accrue due to reduced infiltration This is expected to be in the form of reduced cold drafts and better temperature uniformity in the residence.

Persons attempting to humidify a building to conserve fuel (or for any other reason) must be cautioned against overhumidification. Condensation on cooler surfaces such as windows, doors, walls and roofs may cause wood rot and serious structural damage.

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