Field Studies of Dependence of Air Infiltration on Outside Temperature and Wind*

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*The air infiltration rate, measured in two similar townhouses, is parametrized in terms of wind speed, wind direction, indoor–outdoor temperature difference (*DT*), average rate of furnace firing, and fraction of time that doors are open. An increase of 0.1 exchange per hour is associated with each of the following: (1) an increase in* DT *by 12 °F (7 °C) at low wind speeds, (2) an increase in normally incident wind by 2 mph (3 km/h) at low* DT*; (3) ten minutes per hour of increased front-door opening; (4) the basement door open instead of closed. The wind–temperature interaction is non-linear, which confounds the modeling. The* DT *effect is nearly half due to increased furnace firing, which induces an air flow three times larger than that required for stoichiometric combustion.*

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IMPACT OF INFILTRATION ON GAS CONSUMPTION

Simultaneous measurements of rate of air infiltration and rate of energy consumption for space heating have hardly ever been available in field studies of energy use in homes. Accordingly, Fig. 1 should be of considerable interest. It shows direct evidence that gas consumption is greater, for the same indoor–outdoor temperature difference, when the air infiltration rate is greater.

Figure 1 gives quantitative information about the relative significance of heat losses

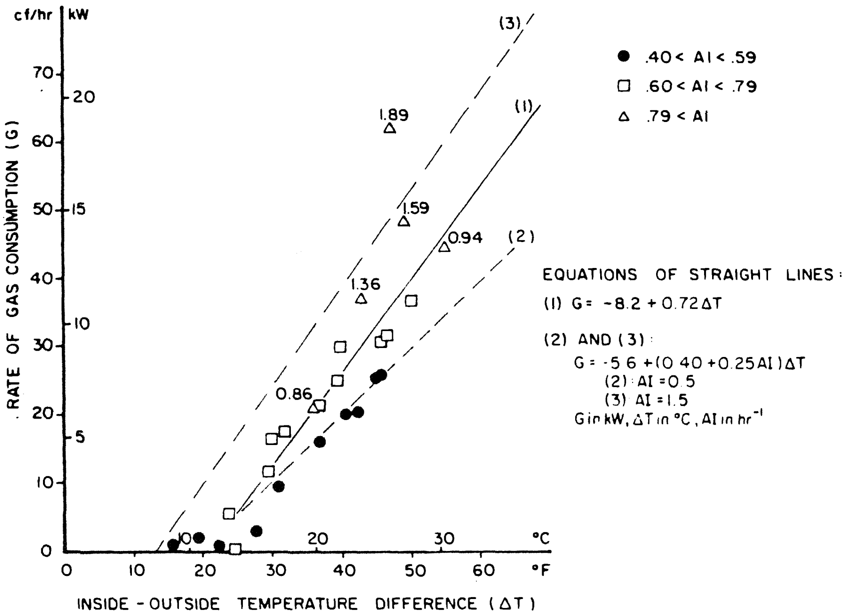

Fig. 1. Furnace consumption *versus* inside–outside temperature difference with air infiltration measured simultaneously. Night-time average values.

due to air infiltration and due to conductance through the shell. Each data point displayed in Fig. 1 corresponds to a different night of data taken in the same Twin Rivers townhouse. For each of 26 nights, measurements were made of the rate of gas combustion (G), the temperature difference between indoors (downstairs hall) and outdoors (DT), and the air infiltration rate (AI), and averages for each night were computed. When a linear model omitting the air infiltration rate was fitted to the data, $G = -\alpha_1 + \beta_1\, DT$, the best fit,

$$G = -8200 + (720 \pm 80)\, DT \qquad (1)$$

had an R^2 of only 0.78 (essentially, left 22% of the variation in G unexplained). Here, G is in W, and DT is in °C. The standard error of the estimate of G for this model is 2300 W. However, when a linear model including the air infiltration rate is fitted to the data, $G = -\alpha_2 + \beta_2\, DT + \gamma_2(AI)(DT)$, the best fit,

$$G = -5600 + (400 \pm 40)\, DT + (250 \pm 20)\,(AI)\,(DT) \qquad (2)$$

had an R^2 of 0.96 and a standard error of only 950 W. Again, G is in W (although originally measured as ft^3 of gas consumed per hour, the gas having an energy content of 1025 Btu/ft^3, or 38 MJ/m^3), DT is in °C, and AI is in exchanges of air per hour. The straight lines corresponding to eqn. (2) with AI = 0.5 h^{-1} and 1.5 h^{-1} are shown in Fig. 1, as well as the straight line corresponding to eqn. (1).

The first term in eqns. (1) and (2) contains the heating by appliances and people, a portion of the heat loss to sinks, like the ground, that are warmer than outside air, and a contribution from heat stored in the structure during the day; it has the physically correct negative sign. The second and third terms represent conductive heat losses and losses due to air infiltration, respectively. Accordingly, the ratio of air infiltration heat loss to total heat loss, may be written:

$$R = \frac{250\, AI}{400 + 250 AI}$$

where AI is in exchanges per hour. For this townhouse, therefore, air infiltration contributes 24, 38, and 48% of the heat loss when the air infiltration rate is, respectively, 0.5, 1.0, and 1.5 exchanges per hour. At the "handbook" constant exchange rate for townhouses, 0.75 exchanges per hour, R is 32%, in general agreement with the rule of thumb that air infiltration typically accounts for one-third of all heat losses in conventional residential housing.

The following sections of this article present the results of an attempt to model the air infiltration rate, as a function of weather and house parameters.

DETERMINANTS OF AIR INFILTRATION — SCOPE OF AN EXPERIMENT

Air infiltration rates were measured over several winter months in two identical Twin Rivers townhouses, with weather variables monitored at a nearby weather station. The geometry of the experiment is found in Fig. 2. Both townhouses occupy interior positions in the row and hence only have two walls exposed to the outside. The two units are oriented nearly at right angles to one another: the axis from the front to the back of the first house is oriented at 15° relative to north. The

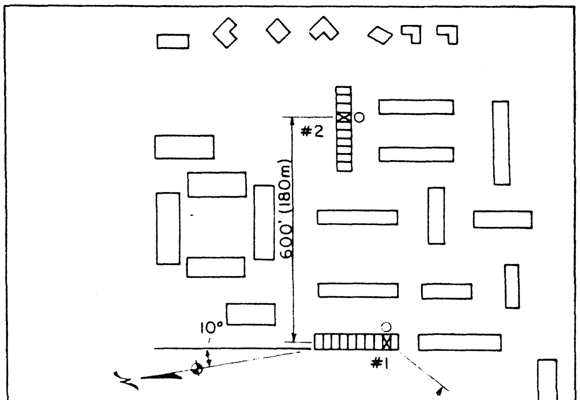

Fig. 2. Plan of Twin Rivers, showing location of experimental houses and weather station.

least shelter from other buildings is found at the back of the first house, and (unfortunately for the occupants) this is the direction (westerly) of the prevailing as well as the highest winds. The terrain is flat.

The air infiltration rate is calculated from the rate of decrease of concentration of a tracer gas (sulfur hexafluoride, SF_6) in the living area. Concentrations are typically about 30 parts per billion at time of injection, and reinjection, in this experiment, occurred every three hours. Experimental details are reported elsewhere [1 - 3].

We have investigated six independent variables as possible determinants of the air infiltration rate. They are:

- DT = temperature difference between indoors (hallway) and outdoors (weather station),
- V = wind velocity (hourly average at weather station),
- θ = wind direction (instantaneous hourly reading at weather station),
- G = rate of furnace gas consumption (hourly average),
- F = front door opening (minutes open during the hour),
- B = basement door opening (minutes open during the hour); basement door opens into the living area.

Results of regression analyses, when particular linear representations of the air infiltration rate were tested, are presented in the next two sections. We use SI units in these expressions; Table 1 should facilitate conversion to American units.

On physical grounds, one should expect the air infiltration rate to increase with wind velocity and temperature difference, but complex interference effects may be anticipated from these two sources of pressure difference over the shell of the house [4]. One should expect, for these townhouses with only two exposed orientations, that wind incident on the house normal to the front and back door should be more effective in creating air infiltration than wind incident from a direction along the building axis. One should expect air infiltration to be enhanced when the furnace is running, because the furnace combustion reduces the pressure in the basement, and combustion air must enter the basement either directly or by way of the living area. The air flow up the flue when the furnace is running is several times that required for combustion, in order to entrain the combustion products, and this flow too must be matched by a corresponding flow into the house from outdoors.

TABLE 1

Conversion of units for variables in this analysis

Variable	Units in this article	Conversion to American units
AI	exchanges of air in "living area" per hour	—
DT	°C	1 °C = 1.8 °F
V	km/h	1 km/h = 0.622 mph
θ	degrees	—
G	kW	1 kW = 3.33 ft^3/h (gas at 1025 Btu/ft^3)
F	minutes per hour	—
B	minutes per hour	—

Of course, one expects the air infiltration rate to be larger, the longer the front door is open, assuming it is open equally wide on all occasions, a quantity not measured. We are actually measuring the air infiltration rate for the living area, a volume that excludes the basement, but there is air flow between living area and basement not only through the basement door but also through leaks in basement ducts and through other passages [5]. The largest effect of the basement door being open, we would expect, is to increase the "stack-effect" pattern of flow, where cold air enters the basement and leaves the house from the living area. There should also be additional air infiltration in the living area when the furnace is running, if the basement door is open. Although these effects suggest models with interaction terms ($DT{\cdot}B$ and $G{\cdot}B$), we have tested more elementary models linear in B, expecting still to see increased air infiltration with the basement door open longer.

All of the effects expected on physical grounds have been found clearly in the data. We have reduced a large number of data sets, each generally associated with a one-week "run" in one house. Only a few runs are discussed here, a larger number elsewhere [2]. We divide the discussion below, somewhat arbitrarily, according to whether the wind speed is low [less than 6 mph (= 10 km/h)] or high [more than 6 mph (= 10 km/h)].

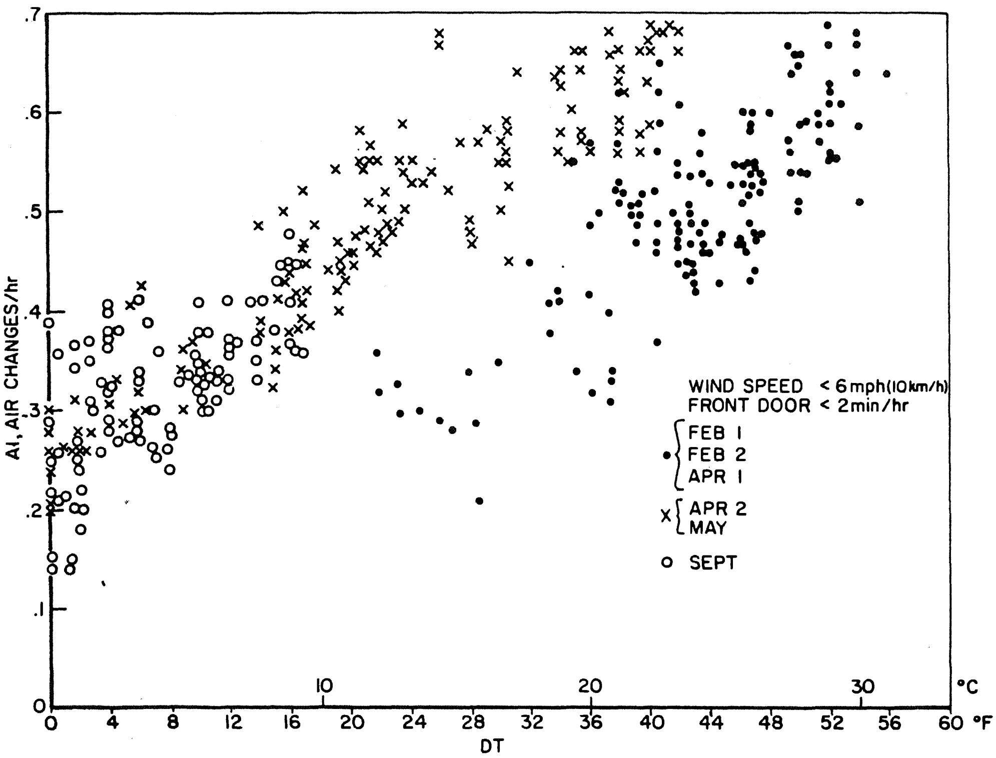

Fig. 3. Air infiltration rate *versus* inside–outside temperature difference — cold and mild weather, house 1.

PARAMETRIZATION OF AIR INFILTRATION RATE AT LOW WIND SPEEDS

Regression analysis

House 1

When we confine the analysis to cases with wind speeds not exceeding 6 mph (10 km/h), here call "low", the effects of wind are minimized. Figure 3 shows a scatter plot of the air infiltration rate, *AI*, against the indoor–outdoor temperature difference, at low wind speeds and with the front door opening restricted to less than two minutes per hour. Each data point is one-hour's data. Six data sets are shown, all from the same house (house 1) but in several different months. Three data sets (FEB1, FEB2, and APR1) follow one trend, the other three follow another.

In both cases, *AI* increases approximately linearly with *DT*, with roughly the same slope, but one pattern is displaced above the other. The house acts as if it had two different "porosities", the house being tighter in one case relative to the other. The higher pattern corresponds to data taken during generally milder weather. It may be that in mild weather, windows and doors are opened rather frequently and are closed carelessly, whereas in winter, people make sure their windows and doors are closed tight.

The mild-weather data sets (APR2, MAY, and SEPT) will not be studied in this article*.

The results of a multiple regression analysis applied to an aggregate of the three cold-weather data sets (with front door opening unrestricted) is presented in Table 2. When only the variable *DT* has entered the analysis, the equation for the air infiltration rate is

$$AI = 0.186 + (0.0148 \pm 0.0018)\,DT \qquad (3)$$

At this stage, four of the five other tested variables are statistically significant. All four

*A confounding variable for two of these data sets (APR2 and MAY) is the presence of a tree barrier on the windward side of the house [6, 7]. We had expected the barrier to reduce air infiltration, but the porosity effect appears to have confounded the analysis. Careful data reduction emphasizing angle dependence at high wind speeds shows an effect of the barrier: 0.2 exchange per hour reduction in air infiltration rate for winds which strike the barrier [2].

TABLE 2

Regression statistics for house 1 at low wind speeds (242 cases: files FEB1, FEB2, APR1)

Variable	Mean	Standard deviation
AI	0.540 exch/h	0.098 exch./h
DT	24.1 °C (43.4 °F)	3.2 °C (5.8 °F)
V	6.03 km/h (3.75 mph)	2.03 km/h (1.26 mph)
$V \mid \cos(\theta - 280°) \mid$	3.89 km/h (2.42 mph)	2.36 km/h (1.47 mph)
G	6.9 kW (23.0 ft^3/h)	3.5 kW (11.5 ft^3/h)
F	0.5 min/h	2.1 min/h
B	7.4 min/h	16.8 min/h

Variable entered	Step-wise statistics			
	Partial F	R^2	Standard error of AI	Overall F
DT	22.0	0.23	0.086	73
G	32.5	0.35	0.080	63
B	34.2	0.43	0.075	59
F	15.9	0.45	0.073	49
$V \mid \cos(\theta - 280°) \mid$	14.2	0.49	0.071	44

survive the significance tests of the multiple regression analysis, which yields:

$$AI = 0.193 + (0.0095 \pm 0.0020)\, DT + (0.0107 \pm 0.0020)\, G + (0.0016 \pm 0.0003)\, B + (0.0088 \pm 0.0022)\, F + (0.0074 \pm 0.0020) \mid V \cos(\theta - 280°) \mid \quad (4)$$

A term linear in V, but angle-independent, is not statistically significant, once the angle-dependent velocity is entered in the regression.

Consider the coefficients of the various terms in the above equation. The coefficient of DT is indicative of the magnitude of the stack effect at low wind speeds. At the mean value of DT (43 °F or 24 °C) the contribution of the stack effect is approximately 0.2 exchanges per hour, 40% of the mean value of the air exchange rate.

The coefficient of G is a measure of the variation of AI with the rate of gas consumption. It indicates that continuous furnace operation (maximum consumption: 75 ft^3 or 2.1 m^3 of natural gas per hour) results in an additional air exchange rate of approximately 0.24 ± 0.05 air changes per hour. When Socolow carried out a similar analysis using data for air infiltration rate and gas consumption taken at 5-minute intervals over a single night, he found that 0.19 air changes per hour were associated with continuous furnace firing [8]. The two results, therefore, are in agreement. Two reasons for an effect of gas consumption on air infiltration are: (1) air is needed for combustion, and (2) air is entrained with exhaust gases going up the flue. Stoichiometric air required for combustion of methane amounts to 800 ft^3/h (23 m^3/h) when the furnace fires continuously. The volume of living space is approximately 10,000 ft^3 (300 m^3). This implies that the supply of stoichiometric air is equivalent to 0.08 air exchanges per hour. Comparing this to the values for continuous firing just presented, we see that about one-third of the induced air due to continuous furnace operation is due to stoichiometric air. The other two-thirds can be accounted for by the entrained air.

The coefficients of B and F are definitely significant. There will be an increase in AI of 0.10 air changes per hour if the basement door is kept open the whole hour, and an additional increase which extrapolates to 0.53 air changes per hour if the front door is kept open the whole hour. Put another way, keeping the basement door open for 60 minutes is like keeping the front door open for 11 minutes (the basement door opens into the interior hallway). In another investigation, we found evidence that the effect of the front door opening is significantly enhanced with simultaneous basement door opening. This could be due to reduction in resistance to air flow from the basement to the living space. It should show up in a term like $F \cdot B$ in a regression analysis, but this has not been pursued.

The fact that the variable V does not enter the regression equation once $V \mid \cos(\theta - 280°) \mid$ is included indicates that, at least in the low wind speed condition, the only component of the wind velocity that has significant effect is the one that is perpendicular to the house row, namely $V \mid \cos(\theta - 280°) \mid$. However, one has to bear in mind that the value of V is restricted to below 6 mph (10 km/h). Moreover, the term $V \mid \cos(\theta - 280°) \mid$ is highly correlated with V. The contribution of the mean value of $V \mid \cos(\theta - 280°) \mid$ to the mean value of AI is found from Table 2 to be equal to only 6%.

Finally, we note that the constant in eqn. (4), 0.193 exchanges per hour, is significantly greater than zero (the standard error being only 0.071 exchanges per hour). Thus, our data suggest that the air infiltration rate approaches a value greater than zero on a mild, calm day when both DT and V approach zero. Hill and Kusuda have anticipated that this effect should be present and that it is related to residual turbulence [9]. Further experimental work near this limit is required, because the implications for public health in tight houses on mild, calm days are significant.

House 2

Figure 4 is a scatter plot, analogous to Fig. 3, but here superimposing four data sets from house 2 on the three data sets from house 1 that have just been studied. The data for house 2 lie above these data for house 1, but not as far above as the "high-porosity" data (from data sets SEPT, APR2, and MAY) shown in Fig. 3.

A regression analysis for house 2 is limited by the absence of instrumentation to detect basement door and front door openings and gas consumption. (For the most part, however, the basement door and the front door were deliberately kept closed during periods of data gathering.) Consequently, only weather variables can be considered.

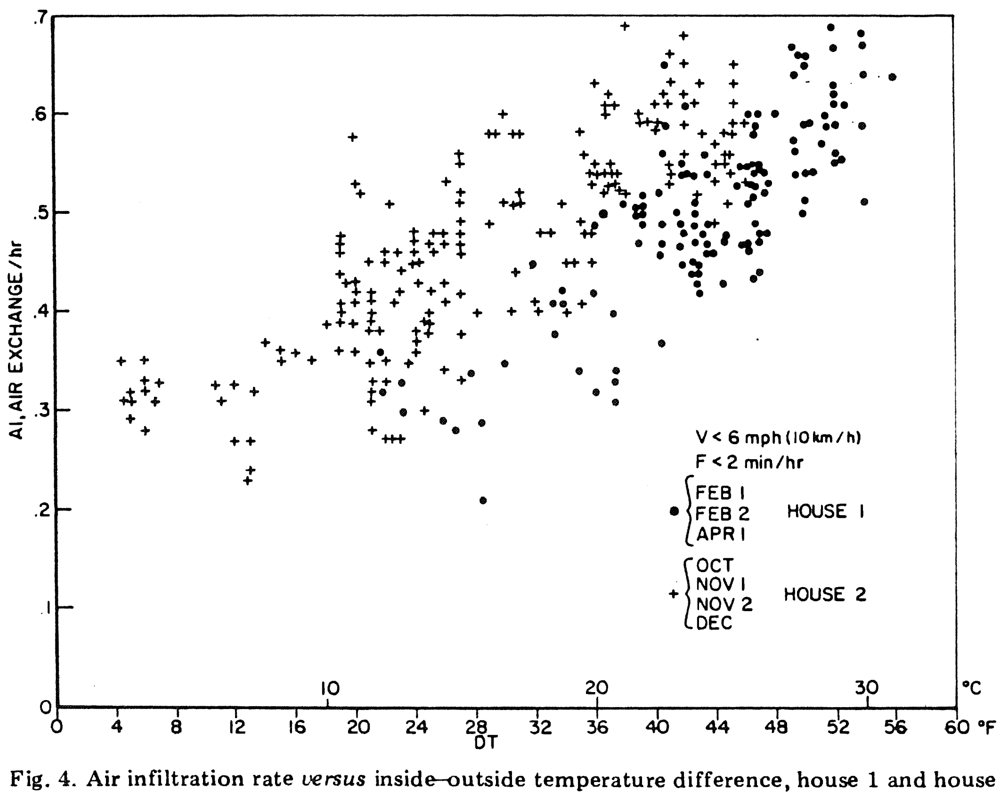

Fig. 4. Air infiltration rate *versus* inside–outside temperature difference, house 1 and house 2.

TABLE 3

Regression statistics for house 2 at low wind speeds (431 cases: files OCT, NOV1, NOV2, DEC)

Variable	Mean		Standard deviation	
AI	0.48 exch./h		0.095 exch./h	
DT	17.5 °C (31.5 °F)		5.1 °C (9.2 °F)	
V	5.23 km/h (3.25 mph)		2.41 km/h (1.50 mph)	
$V \mid \cos(\theta - 15°) \mid$	3.73 km/h (2.32 mph)		2.36 km/h (1.47 mph)	
Variable entered	Step-wise statistics			
	Partial *F*	R^2	Standard error of *AI*	Overall *F*
DT	464.6	0.48	0.069	396
$V \mid \cos(\theta - 15°) \mid$	74.7	0.56	0.063	269

Table 3 shows results of a regression analysis at low wind speeds, when the data sets OCT, NOV1, NOV2, and DEC are aggregated. In this case *AI* can be represented as a function of *DT* by the following equation:

$$AI = 0.26 + (0.0128 \pm 0.0007)\, DT \qquad (5)$$

Here, as in eqn. (3), the coefficient of *DT* represents a combination of the stack effect and the furnace effects. The coefficients of *DT* in the two equations are consistent with one another. This might have been expected, since both houses are of the same type.

When the effect of wind velocity is explored, the data are better explained by a term linear in $\mid V \cos(\theta - 15°) \mid$, the perpendicular component of the velocity, rather than by a term linear in *V*. The same preference was observed in house 1. The resulting equation is:

$$AI = 0.22 + (0.0128 \pm 0.0005)\, DT + (0.0111 \pm 0.0013)\, V \mid \cos(\theta - 15°) \mid \qquad (6)$$

The coefficient of the *V* — dependent term is slightly larger than in eqn. (4) for house 1, but to one standard deviation, the coefficients nearly overlap.

PARAMETRIZATION OF AIR INFILTRATION RATE AT HIGH WIND SPEEDS

We confine our attention to one data set (APR1), obtained in house 1 over a period of six days (April 1 to 6, 1975), during which, for three days, there was an exceptionally violent storm. The hourly average wind speed varies between 3.5 mph (5.6 km/h) and 29.9 mph (48.1 km/h) and the wind direction spans the whole circle. We divide our data set into three subsets, according to whether the indoor–outdoor temperature difference, *DT*, lies between 40 °F (22 °C) and 50 °F (28 °C); between 30 °F (17 °C) and 40 °F (22 °C); or between 18 °F (10 °C) and 30 °F (17 °C). By working within narrow bands of *DT*, we minimize the problems of complex interaction effects between wind and *DT*.

22 °C (40 °F) ≤ DT ≤ 28 °C (50 °F)

There are 63 data points in this subset, and they are shown against wind velocity in Fig, 5, for several ranges of wind direction. Even though in this particular data set there are no easterly winds, Fig. 5 shows clear evidence of the effect of wind direction. For example, at 12 mph (19 km/h) the air infiltration rate is nearly doubled when the wind comes from the rear of the house (data points shown as squares) instead of along a direction parallel to the townhouse row (data points shown as circles).

Ignoring wind direction for a moment, we attempt a fit to the data linear in wind velocity. We obtain:

$$AI = (0.037 \pm 0.003)\, V + 0.21 \qquad (7)$$

The R^2 is 0.69 and the standard error of estimate is 0.22 exchanges per hour. Using a step-wise regression, we find that a term linear in the gas consumption enters next in the equation, giving:

$$AI = (0.027 \pm 0.003)\, V + (0.030 \pm 0.007)\, G + 0.15 \qquad (8)$$

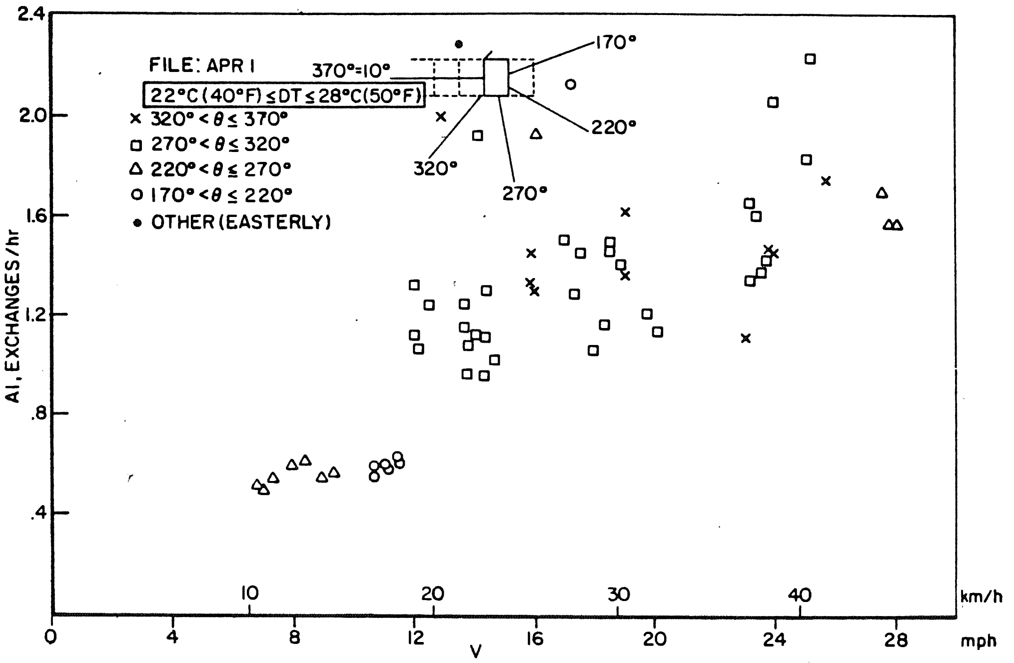

Fig. 5. Air infiltration rate *versus* wind velocity, very cold weather.

The R^2 at this step assumes the value of 0.78 and the standard error of estimate is reduced to 0.19 exchanges per hour. We observe that as G is entered in the equation, the coefficient of V is significantly reduced. Some of the wind effect appears to be due to greater gas consumption in higher winds.

In order to study the influence of wind direction, we plot the residuals (Fig. 6) defined by the difference between the measured value of AI and the value obtained from eqn. (8). Generally speaking, the residuals are positive in the neighborhood of the perpendicular to the row axis (280°) and are negative in the

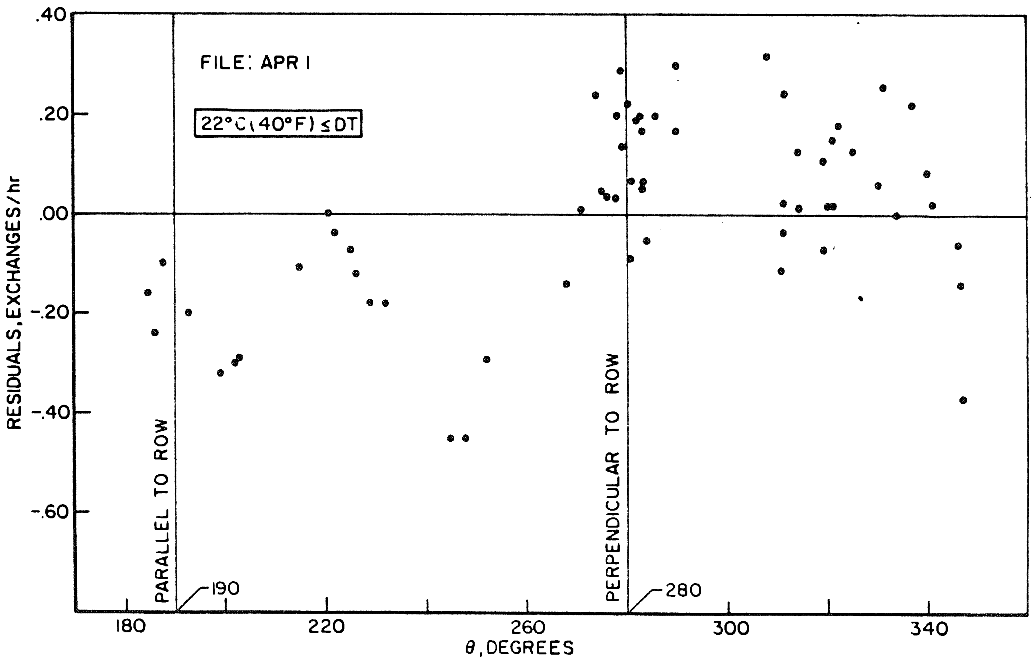

Fig. 6. Residuals of a linear fit to the data in Fig. 5, plotted against wind direction.

neighborhood of the parallel to the row axis. This leads us to approximate the dependence on θ by a sinusoidal function, $V \cos(\theta - \phi)$. The best fit to the data is found for $\phi = 300°$. The fit is significantly better than for $\phi = 280°$, the direction of the perpendicular to the house row axis. (On physical grounds, a term with $\phi = 280°$ was expected to be the more statistically significant. The fact that a term with $\phi = 300°$ has a better fit can either be due to an instrument error, or to the complexity of the wind effect.) We obtain:

$$AI = (-0.002 \pm 0.004)\ V + (0.30 \pm 0.003)G + (0.027 \pm 0.003)\ V \cos(\theta - 300°) + 0.31 \qquad (9)$$

The R^2 increases to 0.91 and the standard error of estimate is reduced to 0.12 exchanges per hour. Comparing eqn. (9) with eqn. (8), we observe that the coefficient of an angle-independent V term becomes statistically insignificant, once an angle-dependent V term is included.

17 °C (30 °F) $\leq$ DT $<$ *22 °C (40 °F)*

As seen in Fig. 7, there are not as many data points at high wind in this data set, compared to the previous data set shown in Fig. 5. However, the ranges of the variables other than DT are largely overlapping, so that an independent parametrization of this data set forms a check on the previous equations. The present data set contains data for easterly winds (the set of points at the lower left in Fig. 7) that will be excluded from the analysis. Figure 7 shows angle-dependent effects (higher air exchange rates for normally incident wind), for example near 18 mph (29 km/h), that are quite similar to those we have observed in Fig. 5.

When we attempt a one-parameter fit to these data, linear in wind velocity, we obtain:

$$AI = (0.032 \pm 0.004)\ V + 0.11 \qquad (10)$$

The R^2 is 0.65 and the standard error of estimate is 0.24 exchanges per hour. As the variable G is introduced in the equation, we obtain:

$$AI = (0.026 \pm 0.004)\ V + (0.027 \pm 0.010)\ G + 0.06 \qquad (11)$$

The R^2 becomes equal to 0.71 and the standard error of estimate is reduced to 0.19 exchanges per hour. The coefficients in eqn. (11) are essentially the same as those in eqn. (8).

When a term incorporating wind direction is included, $V \cos(\phi - \theta)$, the anomalous preference for $\phi = 300°$ rather than $\phi = 280°$ is again observed.

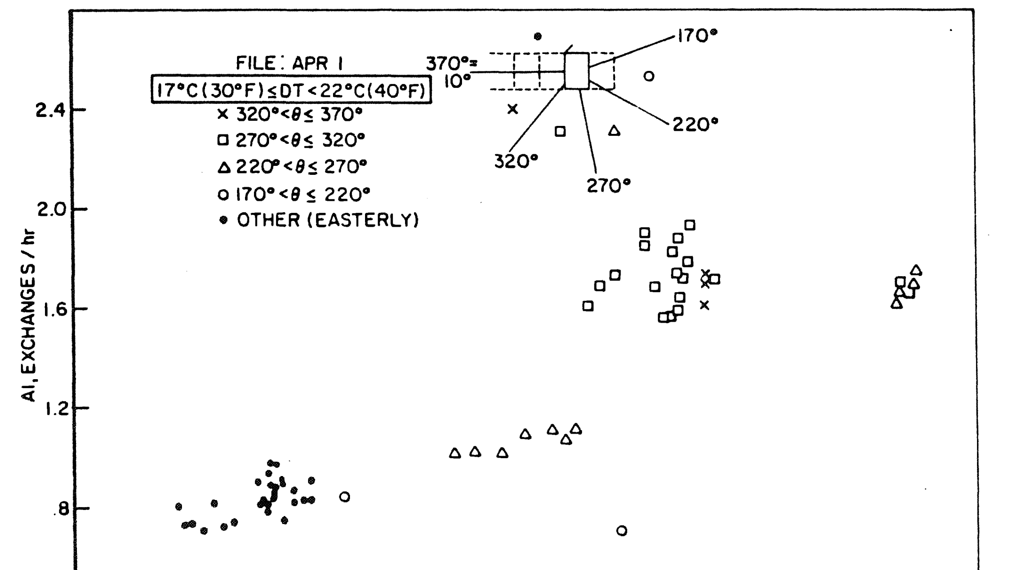

Fig. 7. Air infiltration rate *versus* wind velocity, intermediate weather.

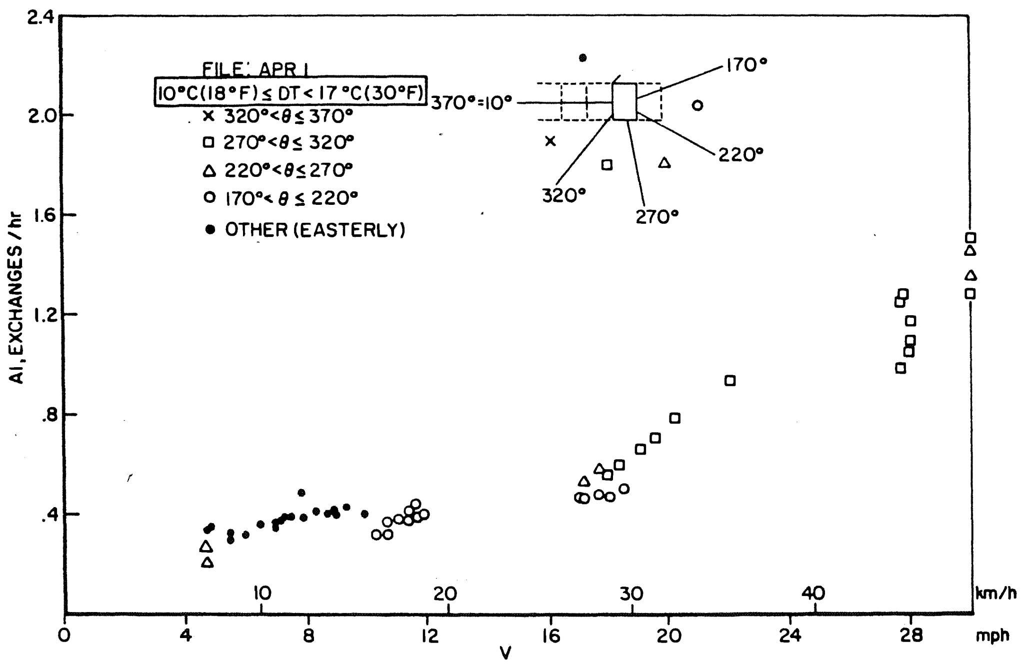

Fig. 8. Air infiltration rate *versus* wind velocity, mild weather.

Analogous to eqn. (9), we obtain:

$$AI = (-0.007 \pm 0.004)\ V \pm (0.007 \pm 0.007)\ G + (0.032 \pm 0.004)\ V \cos(\theta - 300°) + 0.44 \qquad (12)$$

The R^2 increases to 0.90 and the standard error reduces to 0.13 exchanges per hour. Again, as in eqn. (9), the angle-independent velocity term has become nearly insignificant.

The term linear in the rate of gas consumption in eqns. (8), (9) and (11) [but oddly not in eqn. (12)] is more than twice as large as what we found for low wind speeds [see eqn. (4) above]. It is indeed reasonable that the air infiltration associated with a given amount of furnace firing should be larger in windy weather, as wind will increase the entrainment of house air with combustion products on their way out of the flue.

10 °C (18 °F) ≤ DT *< 17 °C (30 °F)*

This mild-weather data set, shown in Fig. 8, is quite small but it shows evidence [for example, near 18 mph (= 29 km/h)] that directional effects of incident wind are less pronounced than in colder weather, an unexpected result that we explore further below. The best fit to this data set analogous to eqns. (9) and (12) above is:

$$AI = (0.010 \pm 0.003)\ V + (0.030 \pm 0.007)\ G + (0.009 \pm 0.002)\ V \cos(\theta - 280°) + 0.14 \qquad (13)$$

Here, there are 41 data points and the R^2 is 0.95. The standard error of estimate is equal to 0.09 exchanges per hour. The angle-independent wind velocity has become more important, relative to the angle-dependent wind velocity. The appearance of the "true" normal to the townhouse, 280°, instead of the value 300° in eqns. (9) and (12), emerged from iterations of the parametrization to increase the goodness of fit, and it remains unexplained. The constant term in the equation is significantly smaller here.

Wind–temperature interaction

The lack of consistency between eqn. (13) on the one hand and eqns. (9) and (12) on the other suggests the existence of a complex interaction between wind and temperature, whose potential existence had been revealed in a theoretical analysis [4]. To see the nature of this interaction for this particular townhouse, we construct Fig. 9, in which we replot the data previously shown in Figs. 5, 7 and 8, this time against DT, with wind velocity restricted to between 10 mph (16 km/h) and 20 mph (32 km/h) and with easterly winds

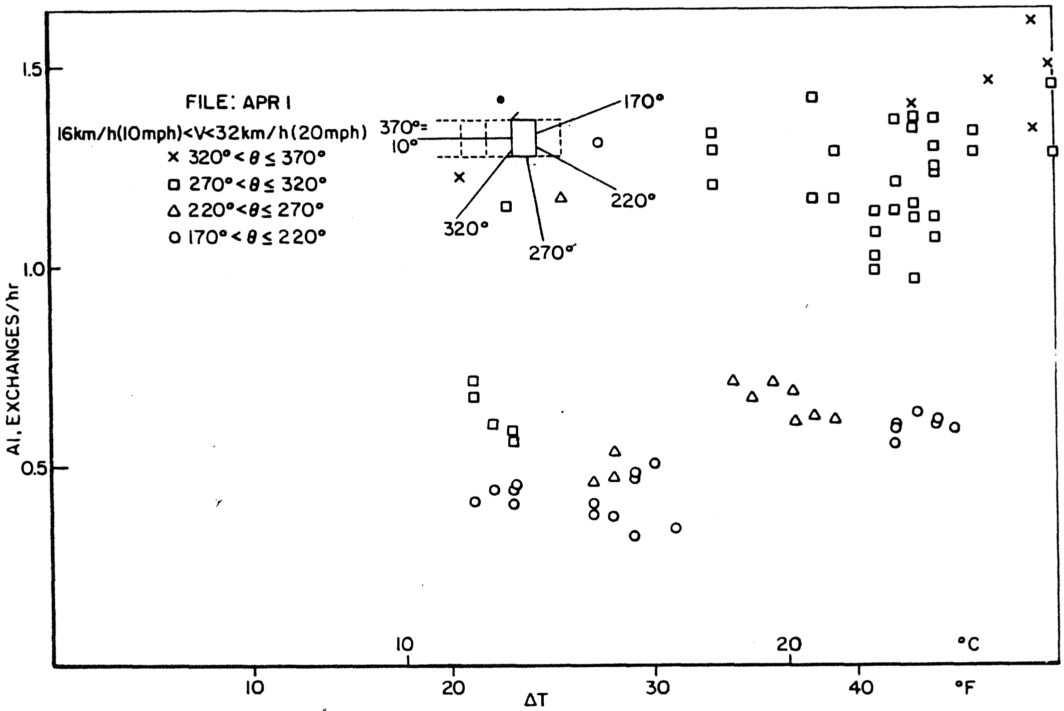

Fig. 9. Air infiltration rate *versus* inside–outside temperature difference for high winds.

excluded. We see clearly that the influence of wind direction, θ, on the air infiltration rate is more pronounced the larger the value of the indoor–outdoor temperature difference, DT.

This suggests that we try to model the wind–temperature interaction using some non-linear parametrization. When we try a term, $DT \cdot V \cos(\theta - 300°)$, which evidently enhances wind effects in colder weather, we find that this captures all of the statistically significant velocity dependence. In a parametrization that also includes a non-linear basement-door term and a furnace term, we obtain:

$$AI = (0.0011 \pm 0.0001)\, DT \cdot V \,|\cos(\theta - 300°)| + (0.023 \pm 0.003)\, G + (0.00014 \pm 0.00005)\, B \cdot DT + 0.30 \qquad (14)$$

There are 144 data points in this regression, all of the data in data set APR1 with westerly wind direction and with DT unrestricted. The R^2 is 0.93 and the standard error of estimate is 0.12 exchanges per hour.

Tests of models beyond their original domain

We have tested the non-linear model, eqn. (14), in several ways. We find that it comes close to predicting the magnitude of the air infiltration rate observed during periods with *easterly* winds of 6 mph (10 km/h) to 10 mph (16 km/h), with the significant exception that the measurements reveal none of the directional dependence predicted by eqn. (14). (The measured rate is essentially constant at 0.4 exchanges per hour.) This may be evidence of the sheltering of this town-house (house 1) by the nearby rows of houses to the east (see Fig. 2).

The non-linear model, eqn. (14), is adequate to predict the air exchange rate for "high" westerly winds in an earlier data set (FEB2). On the other hand, it evidently does not have any smooth connection to the models, eqns. (3) - (6), developed for "low" winds in the previous section. Given that the form of wind–temperature interaction chosen in eqn. (14) *vanishes* at zero wind velocity, it is not surprising that eqn. (14) seriously under-predicts the air infiltration rate observed at low wind speed.

House 2.

Finally, we have examined the high-wind data for house 2, whose orientation differs by approximately 90° from that of house 1 (see Fig. 2). Our data sets contain high-wind data only for southerly winds (the sheltered direction for house 2), none for northerly winds (the exposed direction). Perhaps for this reason, an essentially opposite form of wind–temperature interaction is present in house-2 data sets: the influence of wind speed is *smaller* the higher the value of *DT*. There appears to be a destructive instead of a constructive interaction between pressure difference due to buoyancy (*DT*) and pressure difference due to wind (*V*). As Sinden has shown [4], both kinds of interactions are possible on physical grounds.

A destructive wind–temperature interaction leads to significant energy savings. It is, therefore, well worth pursuing these non-linear effects in the field and in laboratory experiments, to begin to understand their physical origins. At present, we have only the first glimmerings of ideas about how they might arise.

CONCLUSION

The air infiltration rate has been measured in two similar townhouses, using a method based on the detection of a tracer gas (SF_6). The method of measurement yielded reproducible rates of air infiltration within 0.1 air exchanges per hour in any single one-week run, once outside temperature, wind speed, and wind direction were controlled for. At low wind speeds, air infiltration rates were found to increase linearly with decreasing outside temperature, with a slope of approximately 0.008 air exchanges/hour/°F (0.014 exchanges/hour/°C). At high wind speeds, non-linear wind–temperature interactions were observed, which had different forms in the two houses. Nonetheless, clear evidence for the effects of wind on air infiltration rate was obtained, including evidence that the effect of wind is enhanced when the wind direction is perpendicular to the house row axis. In linear regression models, coefficients of either wind velocity or the perpendicular component of wind velocity ranged from 0.03 to 0.06 air exchanges/hour per mile of wind velocity (0.02 to 0.04 exchanges/hour per km/hour of wind velocity).

Additional physical effects could be discerned in multiple linear regression analyses, including increased air infiltration rates for fixed outside temperature and wind when (a) furnace on-time is increased, (b) front door open-time is increased, and (c) basement door open-time is increased. The basement door is an interior door, and result (c) calls attention to the significance of separate zones with distinct air infiltration rates within the house.

The parametrizations presented in this article give glimpses of a set of physical principles at work in determining air exchange rates in a house, that so far are poorly understood. Advice cannot now be given to residents concerning which interior doors to keep closed to reduce air infiltration rates, nor concerning when to open windows so that air infiltration rates do not become uncomfortably *small* in mild weather with low winds, once houses are tightened for cold weather and high winds. Extensive field experience and laboratory modeling would appear to have high priority, to enhance the effectiveness of the world's expanding programs in energy conservation in housing.

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