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Estimating the air change rates in dwellings using a heat balance approach

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Abstract

Infiltration and ventilation rates in domestic buildings vary with construction type, weather conditions and the operation of openings in the fabric. Generating good estimates of ventilation is important for modelling, simulation and performance assessment as it has a significant impact on energy consumption. Physical tests can be applied to estimate leakage, but this is cumbersome and impractical to apply in most cases. This paper applies a heat balance approach to energy monitoring data to estimate a parameter that describes the combined ventilation and infiltration rates in real family homes. These estimates are compared with published values and a model is presented that describes the air change rate as a function of user behaviour (control of openings) and varying wind speed. The paper demonstrates that it is possible to estimate plausible air change rates from such data.

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1. Introduction

In the UK, heating and hot water energy use accounts for about 75% of residential CO₂ emissions and hence reducing consumption is a key component in achieving the UK government's climate change targets. Assessing and estimating building performance and modeling the impact of retrofit measures designed to improve the thermal

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efficiency of buildings, is becoming increasingly important. Models that are applied to assessment in the UK include those built on physical principles and fall in to two board categories: simple physics based models such as BREDEM and the UKDCM or the Community Domestic Energy Model (CDEM) [1,2,3] and more detailed simulation tools such as DOE-2, EnergyPlus, BLAST, ESP-r or TRNSYS [4,5,6]. Although models of occupant behaviour (predominantly for use in simulation; for example [7]) have been developed, naturally driven air change rates, particularly in residential buildings are almost always based on generalised values.

Current models used for the estimation of energy use, therefore do not offer a good representation of air change rate and instead rely on assumptions which do not account for variation in the behavior of the occupants [8]. This becomes problematic when tailoring information to homeowners or estimating the impact of retrofit measures on energy consumption for specific households. Air change rate has a significant impact on energy consumption and it is also dependent on the prevailing weather conditions and the occupants use of door, windows and vents. Since employing physical testing to estimate how air tight existing buildings are is impractical, estimating air change rates using a proxy method is more appropriate for wider scale applications.

This paper explores an approach to estimating domestic air change rates by employing a steady-state heat balance method to monitoring data that can be made available through home energy management systems. The approach is applied to a real UK home and it is demonstrated through comparison to the calculated rates with published data that the resultant estimates are quite plausible and hence the approach could have wide spread application to assist with targeting the correct retrofit measures nationally, as well as being the basis for improving the estimation of air change rates in UK homes for other modelling and assessment applications.

2. Monitoring and test building

The test building was part of a 4 year monitoring study undertaken in the UK to investigate energy demand reduction in family homes. The building is detached and built in the 1950s with minimal insulation, partial double glazing and is not atypical of many homes in the UK. A family of 3 live there and someone is typically home during weekdays. The home is heated via a combi-boiler, has hand operated windows and extract fans fitted in the kitchen and bathroom. The floor plans are depicted in Figure 1: H30 refers to the code given the home within the project.

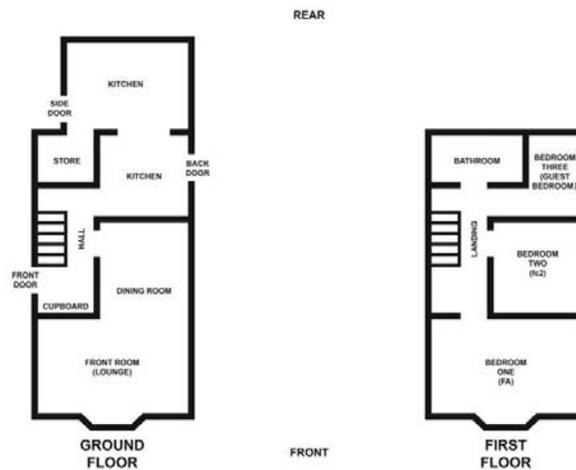


Fig. 1. Floor plans of H30.

The building was monitored between 2012 and 2014: data gathered in 2013 was used in this study. The measurements of power, temperature and door and window opening were made via proprietary, energy/security equipment developed for the home monitoring market. Gas consumption was measured by a bespoke system in this case, but could be replaced by smart meter data. Hot water consumption was also measured using a bespoke system

comprising of an inline flow meter and data logger. Although not routinely measured currently because of installation difficulties, such measurements could be made within combi-boilers in the future, or through after market devices. The cost of measurement is almost certainly going to reduce and become more widespread and hence is not considered prohibitive to the approach described here.

The measured data were sampled ranging between every second to 2 minutes, but all were formatted to a common time step of 1 minute and then aggregated/averaged to daily values for application in this study. The energy balance approach presented here considers daily values and hence valid data of all key measurements were required to be available for a given day. The data was therefore filtered, rejecting days where key data was missing, the analysis the being carried out on the remaining available data-days.

3. The heat balance approach

In the analysis, monitoring data is used to define the energy consumption characteristics of the home. The approach described here is based on a household level steady-state heat balance, aggregated daily. The monitored gas and electricity consumption, internal/external temperatures are combined with estimates of other heat gains and hot water consumption (unless also measured) to generate the heat balance given by,

$$0 = (Q_g + Q_e + Q_p + Q_s) - (Q_w + Q_f + Q_v), \quad (1)$$

where Q_g , Q_e , Q_p , Q_w , Q_f , Q_s and Q_v are the daily sum of gas consumption, electricity consumption, heat gains through people, heating for hot water and solar gains, heat losses due to the fabric of the dwelling, air infiltration and ventilation in Watts [9]. The heat balance can be performed with any amount of data, using averages and multiple days of the year, making the approach quite flexible.

The principles of the energy balance are similar to those found in BREDEM and SAP. The approach presented here decreases the number of assumptions that these methods use in their calculations by using monitoring data to characterize the heat flow via air (Q_v): SAP, for example, uses an average ventilation rate per hour. In this model, Q_v is estimated from the residual in the heat balance calculation process. If the heat loss through air change is significant in buildings, then Q_v must be influenced to some extent. A question to explore here is whether these effects can be observed through the measurement and modeling assumptions.

Once Q_v for a specific day has been established (in W), the air change rate can be determined by,

$$\dot{m}_a = \frac{Q_v}{Cp_a (\bar{T}_{in} - \bar{T}_{out})}, \quad (2)$$

where Cp_a , \bar{T}_{in} and \bar{T}_{out} are the specific heat capacity of air (W/kg K), average daily temperatures inside and outside the building (°C) and the daily mass flow rate of internal, exchanged with the external air (m³/day) respectively. From this, the mass flow rate can be converted to volume flow rate and air changes per hour.

3.1. Parameter definitions and assumptions

Heat gains through space heating, Q_g : the heat input to the space via the heating system is considered to be the total metered gas consumption, factored by the boiler efficiency (taken from, [10]), minus the energy used for hot water. It is assumed that heat from secondary gas appliances (fires, ovens and hobs), results in a gain to the space.

Heat gains through electrical consumption, Q_e : the incoming mains to the property is measured and it is assumed that all electrical energy is converted to heat within the home. Heat generated through extract fans, and other small loads that are rejected from the space are neglected. Electric showers and tumble driers (depending on the amount of use) may also need to be removed from the daily consumption: the electric shower was considered to be significant in this case. It is assumed that washing machine loads (water heating) will not result in significant internal sensible

heat gain since radiator drying will promote latent heat gain, or clothes will be dried outside and waste water will exit the building via the drain.

Heat gains from occupants, Q_p : Occupancy is an important factor in determining energy consumption in homes, but establishing presence of individuals and locating them in homes is challenging and assumptions are inevitable. This is likely to ease as homes become more open to higher degrees of monitoring through personal devices and analysis of appliance use in the home. The approach taken here was to estimate the daily total heat gain from occupants is to base the model input on a simplified representation of daily occupancy:

- *weekday* - house unoccupied during working hours, all at home the rest of the day;
- *working from home* - house continuously occupied by one or more family members during working hours and by the whole family for the rest of the day; and,
- *weekend* - house permanently occupied by the whole family.

These patterns were checked against the measurements in a qualitative sense and appear to be not unrealistic for this home. Clearly however, the imprecision of the input will result in an increase of noise in the estimates of Q_v . Heat gains from occupants are calculated based on a standard metabolic rates: 100W/hour, 85W/hour and 75W/hour for male adults, female adults and children respectively.

Solar gains, Q_s : gains through glazing are estimated applying the BREDEM formula [1] and takes account of variations in solar radiation, shading, orientation and transmission. Gains through opaque elements are neglected.

Heat gains through hot water, Q_w : the heat used for the provision of hot water, is assumed to generate an insignificant increase in sensible air temperature: the effects are localized (typically in the bathroom); a significant proportion of the energy contributes to a latent heat gain; and any gains are mitigated through the brisk extract of air, hence when looking at daily average values these impacts are likely to have a small effect on the measurements. Dwellings with significant numbers of bathing adults might require a reconsideration of this assumption. It applies to energy supplied through electrical power and gas through the boiler. In systems with hot water storage, hot water travelling to an outlet does not fully account for the energy used to maintain water temperatures due to heat loss. Rather than attempt to estimate this, it is assumed that the addition ‘waste’ heat actually results in a sensible heat gain to the space, which is monitored and hence accounted for in the calculation.

Fabric heat conduction, Q_f : heat conduction through the fabric is estimated based on the U-values of the building elements, their areas and difference of temperature based on monitored outdoor temperature and average indoor temperature. Where multiple indoor temperature measurements are made the average is taken and the outside air is measured locally. It is further assumed that effect of heat storage in the mass of the building will be negligible over a 24 hour period in that heating is usually intermittent allowing stored heat to be re-emitted into the space.

Rejecting data-days where $v_{in} - v_{out} < 1.5K$: because the approach relies on temperature difference to calculate the air flow rate, there need to be a significant difference between the daily average internal air temperature and the daily average external air temperature. This was taken to be 1.5K here, which resulted a reasonable number of available days on which to characterise the ventilation rate.

4. The air change rate model

Equation 1 and 2 are used to calculate the average air change rate for each available data-day in 2013. In the building, a number of windows were monitored for being open or closed. It was not practically possible to monitor every window and every door, however this was mitigated to a large extent by identifying the windows that occupants tend to use for ventilation. It was possible then to sum the number of minutes of ‘open window time’ that existed on any given day: this was used as an indicator to determine when the air change rates are likely to be higher. The wind speed was measured from a local weather station and the average wind speed for each day was used to determine any effect. Wind direction, orientation of opening and exposure was not accounted for.

The model air change rate was then calculated by mapping the dependency ventilation rate to wind speed and the window open time through multiple regression to estimate the constants a , b and c in the formula,

$$N = a + b \cdot v_w + c \cdot \$, \quad (3)$$

where N is the average number of air changes per hour (1/hour), v_w is the daily average wind speed (m/s) and $\$$ is the window open time indicator (minutes/day).

5. Results and discussion

Figure 2 depicts the dependencies of air change rate on winds speed and door/window opening time on the top two plots. The lower left hand plot shows the dependency of door/window open time on wind speed, which suggests that the opening time increase with a decrease in wind speed. This might be expected and summer is generally warmer with lower wind speeds and in fact such a relationship was observed in this home. The bottom right hand plot depicts the data and the model based on Equation 3 where the constants a , b and c have the values 1.29, 0.12 and 0.01 respectively. $R^2 = 0.1$ for the model depicted in the bottom right hand plot in Figure 2, which low for typical engineering applications, but the intent here is to generate a model that yields plausible air change rates over a range of conditions. The model does capture important relationships that influence air change rate, but might be expected to be imprecise baring in mind that the calculation is based on average daily values which mask a host of immeasurable factors that are typical in a domestic setting.

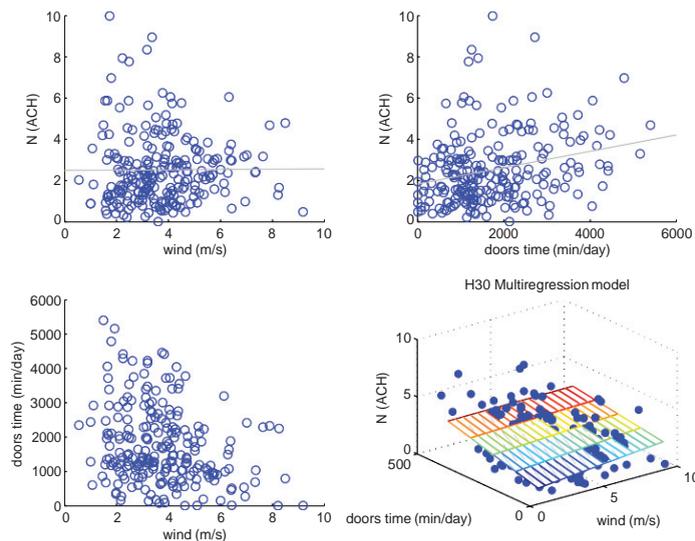


Fig. 2. Dependencies of air change rate in H30 on wind speed and door/window open time in 2013, with the resultant model.

5.1. Calculated values of air change rate

The average daily ventilation rate accounts for the infiltration and natural ventilation of the dwelling and varies between 0.13 Air Changes per Hour (ACH) and 9.98 ACH, giving an average of 2.49 ACH. The range is similar to other previous values published in the literature [11], which reported air changes per hour as low as 0.23 for a sample house when the heating system was off and doors and windows were closed. The higher value also seems to be similar to published values, but possibly towards the lower end of some rates that have been observed [12, 13].

5.2. Air change rate model

In the bottom right hand plot of Figure 2, the plane represents the ventilation model. Extrapolation gives the air change rate at the origin that might be attributed to a baseline infiltration rate. As the wind speed increases, so does

the infiltration rate (when windows are closed). As more windows are open for longer, the air change rate increases. The highest rate occurring on the windiest days, with the greatest window open time, as might be expected.

In terms of the performance of the model to be used to predict energy consumption, if Equation 1 is rearranged to calculate Q_g , and the model given in Equation 3 applied to estimate Q_v , the analysis can be rerun on data from a similar property (H01, in this case) to predict the gas consumption of the building: within 5% of the measured consumption, which is positive, however in 5 other homes the prediction accuracy varied from 14% to 55%.

One issue is the noise in the data arising from the assumptions in the model and the uncertainties in the measurements, resulting in low R^2 values. The fit of the model tends towards a flat plane, which has the effect of averaging the results somewhat and results in the fairly high constant for a of 1.29.

6. Conclusions

A heat balance approach to estimating air change rates in domestic buildings was presented as an alternative to carrying out the physical testing. The residuals from the calculation generated plausible air change rates that were comparable to those observed by others. A model based on these estimates was found to capture, at least qualitatively, expected characteristics that related air flow rate to wind speed and in the opening of doors and windows, albeit with a tendency average ventilation rates across the modeled parameter space.

For studying energy consumption aggregated over extended periods the effects of this averaging is mitigated to a large extent. The approach can therefore be used for generating estimates of energy loss due to ventilation for application in reduction analysis for specific buildings. For estimating ventilation and infiltration rates, however, further work is needed to reduce the noise from measurements and assumptions in order to generate a better model.

With the growth in home monitoring systems, a simple approach that can utilize this data for estimating 'hard to measure' building characteristics is potentially extremely useful. This approach shows some promise and could be applied to tailoring and advice for potential savings from retrofit measures in addition to informing building energy performance assessment and modelling.

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