Topic C1: Respiratory infection in indoor environment

TUBERCULOSIS TRANSMISSION: MODELLED IMPACT OF AIR-TIGHTNESS IN DWELLINGS IN THE UK

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SUMMARY

High CO_2 emissions from the residential sector have forced UK authorities to promote measures to improve energy efficiency through retrofit. Air-tightening can reduce infiltration rates, thereby decreasing ventilation heat losses, but also reducing indoor air quality. This paper presents an initial investigation of the increase in airborne transmission risk of Tuberculosis (TB) due to air-tightening in two of the most commonly-occurring dwelling types in London (purpose-built flat and terraced). EnergyPlus is used to calculate the ventilation rate of the main bedroom over a year for a range of building permeabilities representing the current and air-tightened stock. The Wells-Riley equation is then used to calculate the risk of infection under three different rates of TB generation. Results indicate the potential for increased airborne TB transmission between building occupants following air-tightening, with occupants of flats more susceptible to infection, particularly at high TB generation rates.

INTRODUCTION

The UK Government aims to reduce Greenhouse Gas emissions by 80% by 2050 (DECC, 2012). Twenty five percent of these emissions are from dwellings, primarily due to space heating. To achieve this target, a series of energy efficiency strategies have been introduced. The housing energy efficiency strategy for England will entail interventions affecting almost all of the 22.3 million dwellings (Davies and Oreszczyn, 2012). Some of these measures include energy efficient refurbishment programs such as the Warm Front scheme (e.g. Hutchinson et al., 2006) that have mainly focused on reducing heat loss through the building fabric. Such interventions have the potential to considerably reduce CO_2 emissions through the efficient use of energy and the reduction of ventilation heat losses.

Air-tightening, including draught-proofing, sealing and insulating ground floors, cavity wall insulation, and the reduction of vents and flues can reduce infiltration rates. Improvements have been shown to increase the air-tightness of UK buildings by between 24 to 71%, thereby reducing ventilation heat losses by up to 30% (Hong et al., 2004). However, this may also have a significant effect on indoor air quality due to the reduced air change rate, leading to increased concentration and exposure to airborne pollutants such as particulate matter (Shrubsole et al., 2012), moisture associated pollutants (Altamirano-Medina et al., 2009), and radon (Milner et al., 2014). In addition, reduced air change rates may lead to the increased transmission of airborne diseases such as tuberculosis (TB), influenza, and rhinovirus. TB transmission is primarily airborne, transmitted through air in droplets nuclei containing *M. tuberculosis,* which can cause infection when inhaled (Riley et al., 1978). When coughing, sneezing, talking or breathing, humans generate an enormous number of droplets, which can remain in the air, settle on surfaces or become attached to other aerosolised particles. Droplets have the capacity to travel significant distances on air currents, and those contaminated with TB can remain infectious over long distances and time (Atkinson et al., 2009).

TB has increased in the UK at a steady rate since 2005 and has become a key health priority, with the prevalence of individuals infected with active TB in the UK currently estimated as 13.9 per 100,000 people (HPA, 2013). London is particularly affected, with a rate of 41.8 per 100,000 – one of the highest TB rates among the capital cities in Western Europe, attributed to an increasingly foreign-born population and poor, overcrowded housing conditions (Zumla, 2011). An individual with active TB may infect 10 – 15 (or more) people a year (WHO, 2010), and while largely treatable – the rate of death of infected individuals is about 4% (Lawn and Zumla, 2011) - the rise of multi-drug resistant TB means that the disease remains a significant public health issue (Anderson et al., 2013). This paper describes the modelling of TB infection risk following air-tightening of two typical London dwellings, including the development of suitable building archetypes, the modelling of these archetypes in EnergyPlus, and analysis of the airflow results to estimate the risk of infection.

METHODOLOGY

Building Archetypes

A 1902-1913 terraced dwelling and a 1960-1979 purpose-built flat were modelled in this study, as they represent the most frequently occurring house and flat types in the London building stock (15.4% and 5.7% of the total building stock respectively, estimated from the frequency of occurrence in the Cities Revealed building stock data for the Greater London Area (GLA) (GG, 2010)). Archetypes representative of these dwellings were taken from the work of Oikonomou et al. (2012). The modelled dwellings can be seen in Figure 1.

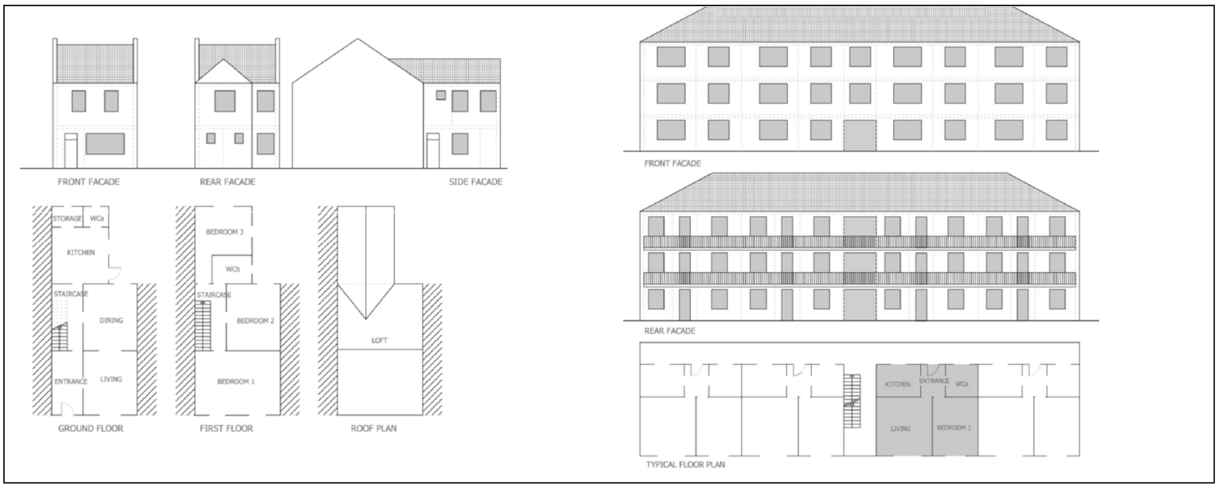

Figure 1. The 1902-1913 terraced dwelling (left) and a 1960-1979 purpose-built flat (right).

A range of building permeabilities was used to represent the distribution of the current building stock (Stephen, 2000), and the estimated performance of the stock in the future following tightening of the building envelope (Milner et al., 2014). The distributions of permeabilities for current and future scenarios are shown in Figure 2. Archetypes were modelled both with and without trickle vents.

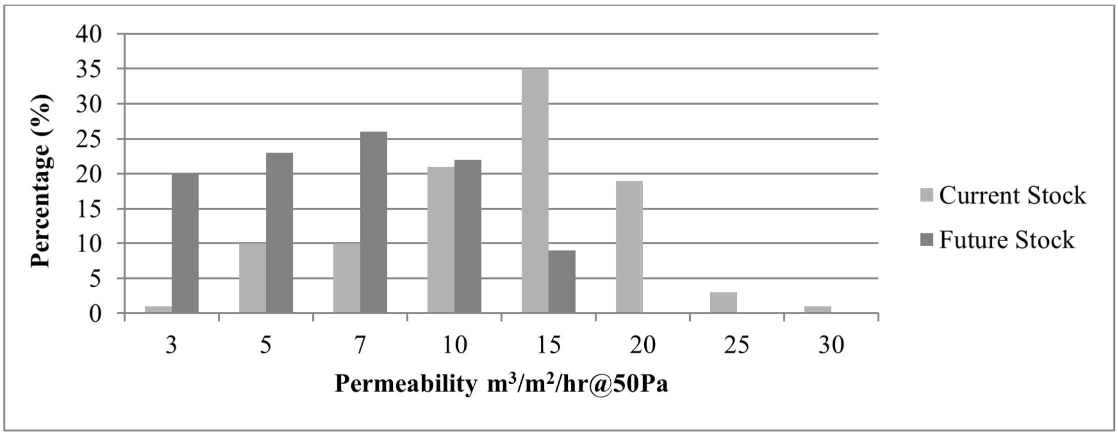

Figure 2. The distribution of building permeabilities for the current stock, and estimated permeabilities for the future stock using methods from (Milner et al., 2014). Future permeabilities are estimated based on regulations for new builds in the UK and empirical evidence in new and retrofitted stock.

EnergyPlus Modelling

EnergyPlus 8.0, a whole-building simulation tool, was used to model airflows in the dwelling archetypes (US-DOE, 2013) using the Airflow Network module. EnergyPlus was used as it contains a coupled dynamic thermal and airflow module, allowing occupant window-opening behaviour in response to changes in internal temperatures. A limitation of such multizonal models is the inability to account for proximity of infectious individuals to those at risk of infection, for which more detailed airflow models are more appropriate. However, previous studies have demonstrated a good agreement between multizonal and CFD simulations in airborne infection risk models (Noakes et al, 2004), while multizonal requires less computational resources to run.

Buildings were modelled at four different orientations (North, West, South, and East), with solar and wind shading applied to party surfaces as appropriate. Building fabrics were modelled with U-values representative of the archetype age classifications, derived using the Government's Reduced Standard Assessment Procedure for Energy Rating of Dwellings (SAP) (BRE, 2009) as per Mavrogianni et al (2012), with the assumption that buildings are as-built under the current scenario and retrofit under the air-tightened scenario. A total of 128 buildings (2 buildings x 4 orientations x 8 permeabilities x 2 trickle vent levels) were simulated.

Internal temperatures were calculated dynamically for a full year. A setpoint of 20 °C was used during the heating season. Windows were modelled to open when indoor operative temperatures rose above 25 °C during the day (07:00-22:00) and 23 °C in the bedroom at night (22:00–07:00), consistent with the temperature thresholds defined in CIBSE Guide A (CIBSE, 2006) and previous modelling work (Mavrogianni et al., 2012). In both cases, the windows remain closed if the external temperature is greater than the internal temperature. Simulations were run under a Typical Reference Year (TRY) weather file for London Heathrow (CIBSE, 2010); the terrain was considered to be 'urban'.

The Airflow Network module was used to model airflow into and within the buildings. Infiltration of air was modelled through cracks in the externally exposed facades (walls, roofs, and ground floors) and windows when open. Internal doors were modelled as being open during the day and closed at night. The distribution of permeabilities around the envelope was modelled as in Shrubsole et al. (2013); readers are referred to this paper for further detail.

The main bedroom was chosen as the location of interest within the dwellings, as it is where individuals are likely to spend the most amount of time in prolonged close contact. The bedroom ventilation rate includes unconditioned air infiltrating into the bedroom from outside, as well as the mixing of uncontaminated, conditioned air from other zones in the dwelling. The average volume of infiltrating and mixing air entering the bedroom was calculated for each minute and output from the EnergyPlus models hourly for a year.

Risk of Infection

A SAS (SI, 2013) routine was used to import the outputs of the EnergyPlus models and calculate the risk of TB infection in the dwellings at night (22:00–07:00). The probability of transmission inside the bedroom was calculated using the Wells-Riley equation:

$$P = 1 - \exp\left(\frac{-Iqpt}{Q}\right) \tag{1}$$

where P is the probability of infection, I is the number of infectious individuals, q is the rate at which infectors generate infectious doses, p is the pulmonary ventilation rate, t is time spent in the zone, and Q is the zone air ventilation rate. For this study, there was assumed to be one infected individual in the main bedroom. Three infectious TB aerosol generation rates (quanta production rates, q/h) were tested. Quanta refers to the number of infectious airborne particles required to infect, and may be one or more particles (Riley et al., 1978). A production rate of 1.25 q/h for an average TB patient was compared with two relatively high quanta production rates of 6 q/h and 60 q/h, and the respiration rate was assumed to be 0.01 m^3/min (Beggs and Noakes, 2003). The probability of infection was calculated for each night during the year, and the yearly average night-time risk for each dwelling variant determined. The calculated infection risks were compared between buildings with different permeabilities, built forms, under different seasons, and with and without trickle vents.

RESULTS AND DISCUSSION

As expected, the risk of infection increased in more air-tight buildings. Figure 3 illustrates the probability of infection inside the dwelling archetypes as the permeability increases for buildings without trickle vents. At high quanta generation rates, the permeability only had a small influence on the probability of infection, while at low quanta generation rates the air-tightness of the building has a more significant effect. There was a steeper decrease in the probability of transmission in terraced properties as permeability increased, likely due to the higher level of infiltration typically observed in buildings with more externally exposed surfaces.

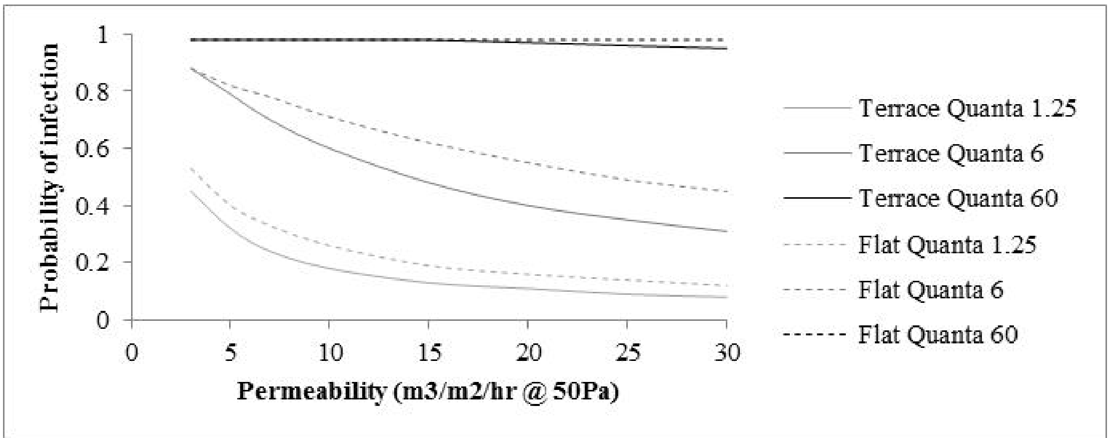

Figure 3. The change in probability of infection as the permeability increases for the building archetypes at three quanta generation rates (no trickle vents).

The estimated probability of transmission in the two dwelling types under current and future air-tightness scenarios can be seen in Figure 4. The results indicate that there is an increased risk of infection in the future due to the tightening of the building stock. The presence of trickle vents decreased the probability of infection but increased ventilation heat loss, thereby losing some of the energy advantages of air-tightening.

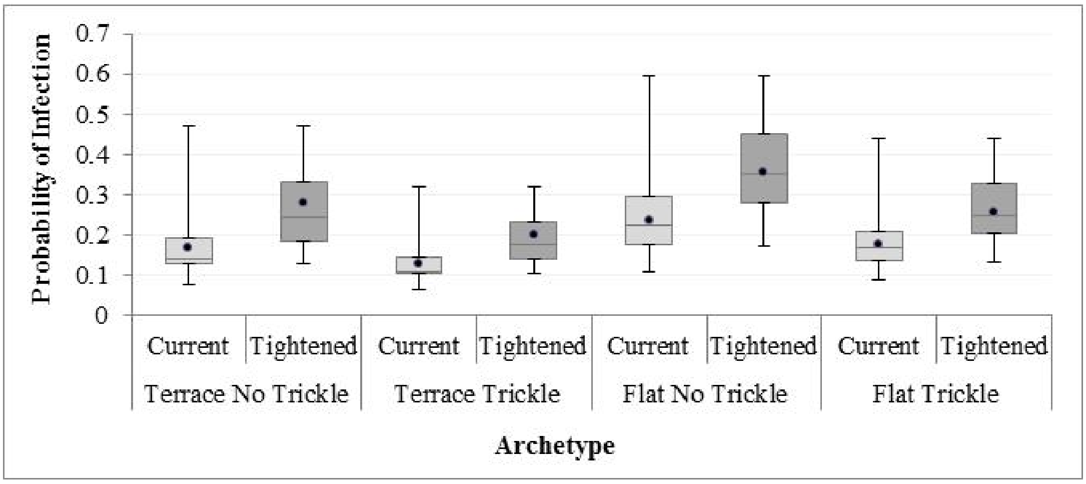

Figure 4. Box and whisker plots illustrating the estimated mean (•), median(-), quartile range, minimum, and maximum TB infection probability in the two archetypes, based on the modelled permeability distributions (TB generated at 1.25 quanta).

The monthly variation in infection risk for the two dwelling types (no trickle vents) indicated a 19% increase in the mean risk of transmission in terraced dwellings and 34% in flats during the months in spring and autumn relative to the summer and winter. This is attributable to a 23% drop in wind speeds in comparison to winter (leading to lower levels of infiltration of external air), but temperatures not being warm enough during the spring and fall to result in increased ventilation through window-opening.

The results of this study suggest that occupants in flats may be at increased risk of disease transmission due to limited ventilation potential. The 1960-1979 purpose-built flat is representative of a large component of the social housing stock in London, meaning occupants of such dwellings may already be at elevated risk of TB or TB exposure. While the results have been demonstrated in the context of TB, the conclusions can be generalized to describe the transmission of any airborne disease.

This work is largely illustrative of the relative risks of transmission between two dwelling archetypes pre and post-energy efficient retrofit. Study limitations are acknowledged, including the assumption of complete air mixing, and ignoring the proximity of infectious individuals to uninfected and at-risk individuals in the same room. The Wells-Riley equation is applied in a deterministic manner, with the assumption of a single infectious individual in the bedroom with a constant production of quanta, and does not consider other individuals becoming infectious and producing quanta themselves. Stochastic modelling techniques are considered to be more appropriate for modelling transmission risk in small numbers (Noakes and Sleigh, 2008), however a deterministic method was used in this study due to the assumption of a single infectious individual and no new infections during the night, and the fact that the results are generalized across a building stock. The probability of infection in other zones is not considered. Infective particle loss through, for example, deposition on surfaces or biological decay is not considered in the Wells-Riley equation. Disease transmission may also occur through non-aerosolised pathways, such as through direct contact; this is not considered in this model.

Home energy efficiency measures that reduce energy loss by limiting uncontrolled ventilation have the potential to increase the transmission of airborne infectious diseases such as TB if additional controlled ventilation is not provided. In particular, residents in overcrowded dwellings or dwellings with limited ventilation potential (for example restricted window openings) may be at particular risk of contracting TB following building retrofits. While building design is secondary to public health strategy in reducing TB prevalence, a change in air-tightness across the building stock may increase the TB and other respiratory disease-related burden. Increasing passive ventilation occurs at the cost of increased energy loss, undermining CO_2 reduction goals in the domestic sector with implications for housing energy efficiency and current UK policy. Heat recovery ventilation systems are likely to provide the best option for energy and indoor air quality.

CONCLUSIONS

This paper represents an initial investigation into the relative risks of airborne disease transmission in dwellings typical of the UK stock under current and air-tightened scenarios. This work has demonstrated how current policy designed to increase the air-tightness of the domestic stock may have the unintended consequence of increasing TB transmission amongst building occupants. We have shown that the risk of TB transmission may increase considerably when infiltration rates are reduced as a measure to improve energy efficiency of residential buildings. This work has also demonstrated that there may be an increased risk in dwelling types with limited levels of passive ventilation such as flats. The trade-off between health and climate mitigation needs to be acknowledged and has implications for current UK energy efficiency policy. Further research will quantify the risk of transmission of a number of airborne infectious diseases for different building typologies on a regional and national scale in order to estimate the increase in respiratory health risks due to the decarbonisation of the building stock.

REFERENCES

Altamirano-Medina H, Davies M, Ridley, I, Mumovic, D, and Oreszczyn, T (2009) Guidelines to Avoid Mould Growth in Buildings. *Advances in Building Energy Research*, **3(1)**, 221-236.

Anderson LF, Tamne S, Watson JP, Cohen T, Mitnick C, Brown T, Drobniewski F, Abubakar I. (2013) Treatment outcome of multi-drug resistant tuberculosis in the United Kingdom: retrospective-prospective cohort study from 2004 to 2007. *EuroSurveillance*, **18(40)**, pii=20601

Atkinson J, Chartier Y, Silvia C, and Jensen P (2009) Natural ventilation for infection control in health-care settings, World Health Organization, Geneva

Beggs, CB, Noakes, CJ, Sleigh, et al (2003) The transmission of tuberculosis in confined spaces: an analytical review of alternative epidemiological models. *International Journal of Tuberculosis & Lung Disease,* **7**, 1015-1026.

BRE (2009) The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Watford, UK.

CIBSE (2006) Guide A. Environmental design. The Chartered Institution of Building Services Engineers, London.

Davies M, and Oreszczyn T (2012) The unintended consequences of decarbonising the built environment: A UK case study. *Energy and Buildings*, **46**, 80-85.

DECC (2012) The Energy Efficiency Strategy: The Energy Efficiency Opportunity in the UK, London.

GG (2010) Cities Revealed Building Class Database, The Geoinformation Group, Cambridge, UK.

Hong S, Ridley I, Oreszczyn T, and Warm Front Study Group (2004) The impact of energy efficient refurbishment on the airtightness in English dwellings. 25th AVIC Conference, Brussels, Belgium, 15-17 September 2004, vol. 1, pp. 7–12.

HPA (2013) Tuberculosis in the UK: Annual report. Health Protection Agency, London.

Hutchinson, EJ, Wilkinson, P, Hong, SH and Oreszczyn, T (2006) Can we improve the identification of cold homes for targeted home energy efficiency improvements? *Applied Energy*, **83 (11)**, 1198-1209.

Lawn, SD, Zumla, AI (2011) Tuberculosis. *Lancet*, **378**, 57-72.

Mavrogianni A, Wilkinson P, Davies M, et al (2012) Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. *Building and Environment*, **55**, 117–30.

Milner J, Shrubsole C, Das P, et al (2014) Home energy efficiency and radon related risk of lung cancer: modelling study. *BMJ*, 348, f7493

Noakes C, Beggs C, and Sleigh PA (2004) Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: comparison of analytical and CFD methods. *Indoor and Built Environment*, **13**, 477‑488.

Noakes C and Sleigh P (2008) Applying the Wells-Riley equation to the risk of airborne infection in hospital environments: The importance of stochastic and proximity effects. Indoor Air: 11th International Conference on Indoor Air Quality and Climate, Lyngby, Denmark, 17-22 August 2008.

Oikonomou E, Davies M, Mavrogianni A, et al (2012) Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. *Building and Environment*, **57**, 223–38.

Riley EC, Murphy G, and Riley RL (1978) Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology*, **107(5)**, 421–32.

Shrubsole C, Ridley I, Biddulph P, et al. (2013) Indoor PM2.5 exposure in London's domestic stock: Modelling current and future exposures following energy efficient refurbishment. *Atmospheric Environment*, **62**, 336–43.

SI (2013) SAS software: version 9.3. SAS Institute, Cary, NC.

Stephen R (2000) Airtightness in UK Dwellings. Building Research Establishment, Watford.

US-DOE (2013) EnergyPlus V8. Washington, D.C.

WHO (2010) Tuberculosis Fact Sheet. World Health Organisation, Geneva.

Zumla, A (2011) The white plague returns to London. *The Lancet*, **377(9759)**, 10-11.