Heating and cooling potential of roof space air: implications for ventilation systems

Final Report

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Executive Summary

This report summarises research carried out at the University of Otago into roof space temperatures in New Zealand houses. New Zealand's most common type of residential ventilation systems are positive pressure ventilation systems that draw air from roof spaces. The heating and cooling potential of roof space air using positive pressure ventilation systems was the focus of this research.

This report presents the results of computer modelling, which used weather station measurements to calculate the amount of heat that could be transferred into the living areas of houses. The model was cross-checked with measured temperatures from within three single-level houses in Dunedin, New Zealand.

It was found that small potential heating and cooling benefits were possible at certain times from pumping air from the roof space into the living areas of some New Zealand houses. However those potential benefits were not large enough to significantly alter the indoor air temperature on average. In 2008, ten-day periods in January, April, June and September were modelled to represent each of the four seasons. The maximum cooling potential of pumping cool air down from the roof cavity was around 1 kW. The maximum heating potential was only 0.52 kW, which is approximately equivalent to the heat output from five 100 watt light bulbs. The majority of the time, it was calculated that pumping air from the roof space into the house would provide no heating or cooling benefit. In fact, this would often actually act to push the internal temperature further away from the desired level rather than closer to it.

Based on the modelling work detailed in this report, it is therefore recommended that existing positive pressure mechanical ventilation systems should not be promoted and marketed on their heating and/or cooling potential. The health and comfort benefits of using roof space air as a means of household humidity control have not been investigated in the current research. Other potential concerns with interchanging roof and living space air, such as fire/smoke hazards and New Zealand building code requirements, have also not been taken into consideration in the current research. These factors should all be fully investigated in future research before determining the suitability of positive pressure roof cavity mechanical ventilation systems to New Zealand conditions.

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1 Introduction

Many different mechanical home ventilation systems have appeared on the market in New Zealand in recent years. The roof surfaces of many existing New Zealand houses represent a large solar collecting area, which can act to heat the roof space air. Several retailers of mechanical home ventilation systems claim possible heat benefits to New Zealand homes from moving air that has been warmed in the roof space into the occupied parts of a house (McChesney, 2009). Similar claims are now also being made about the potential for cooling benefits from these systems as well. However, these claims do not appear to be based on independent scientific measurements or modelling. This report outlines research done at the University of Otago Physics Department to help fill this gap.

McChesney (2009) estimated that around 10% of New Zealand homes had some form of mechanical ventilation system installed. Positive pressure roof cavity systems made up the majority of these systems. Positive pressure roof cavity systems pressurise the house slightly by pumping filtered air down from the roof space. Air flow is induced through gaps and leaks in the building envelope as a result of the pressure difference between inside and outside. The other main types of mechanical ventilation system marketed in New Zealand are balanced pressure heat recovery systems. These systems have two fans, one of which draws in fresh air from outside while the other exhausts an equal volume of indoor air to the outside. These two air streams are kept separate but interact thermally in a heat exchanger to help reduce heating/cooling loads. This report focuses solely on positive pressure roof cavity systems.

The purpose of the research described in this report was to investigate the energy/heat balance of New Zealand roof spaces, and specifically to establish whether this energy can be used to help heat and/or cool the building envelope. The timing of these energy/heat fluxes must also be taken into account to assess the diurnal and annual variability in both roof space solar gains and the building's heating and cooling requirements.

2 Methodology

Temperature and humidity measurements were recorded in the roof spaces and occupied spaces of three Dunedin houses for periods between December 2007 and July 2009. A mathematical model was developed to independently predict the temperature in the roof space and occupied areas of the house. Measured and modelled results were compared to assess the model's accuracy, therefore allowing it to be run for other locations around New Zealand.

2.1 Measurements

If carried out over a long enough period, direct measurements of air temperatures and humidity in the roof spaces and occupied spaces of an individual house can be used to assess the possible effectiveness of a mechanical ventilation system for heating that particular house. The aim of the measurements made in this research was to validate modelling work, so that more general predictions could be made on the ability of mechanical ventilation system for heating and cooling houses in different locations.

Direct measurements of air temperatures and humidity were recorded in the roof spaces and occupied spaces of three Dunedin houses for periods between December 2007 and July 2009. One of the houses had a mechanical ventilation system installed and operating for most of the monitored period, while a neighbouring house had only passive ventilation. These two houses are denoted DUD1 and DUD2 in this report. DUD1 and DUD2 were both four-bedroom, detached, single-story houses, of timber-frame construction. Roofing was corrugated iron, painted charcoal in colour. The houses were oriented with their living rooms facing approximately north-west. Locally, such houses are referred to as "villas". The houses dated from prior to 1914, although both had undergone internal modifications, such as replacement of some of the original wooden sash windows with aluminium windows. As is common in New Zealand, all windows were single-glazed. The houses originally had no insulation in the roof, walls, or under the floor. The houses had relatively recently had fibreglass batt insulation placed in the roof space, and subsequently recycled (sheep) wool insulation had been blown into the roof space. A third house, denoted DUD3, also without a mechanical ventilation system, was located approximately 2 km from the other two houses and was monitored independently. DUD3 was constructed prior to 1929, and was also a villa of similar construction and size to DUD1 and DUD2. Measured data from these houses was then used to validate the modelling described below.

The temperature and humidity was recorded in houses DUD1 and DUD2 at specific locations in the roof space, hallway, and living room, using two different measurement devices.

Thermochron iButtons (DS1921) were used to measure and record the temperature at the installed location with a sampling interval of between five and thirty minutes. Onset HOBO data loggers (H08 series) had a similar sampling frequency to the iButtons and were used to record both temperature and humidity. Checks on the tracking of sensors were carried out in a controlled environment chamber. A HOBO and an iButton were installed next to each other at each location to provide redundancy and allow sensors to be cross-checked with each other. The hallways and living rooms of both houses had sensors installed at three different heights, which were approximately 0.4 m, 1.6 m, and 2.4 m above the floor. Roof space sensors were paired up where possible and installed in convenient places at various heights between 6% and 83% of the roof cavity height above the installed insulation. Hygrochron iButtons (DS1923) were used to record both temperature and humidity for a single location in the roof space, hallway, bedroom, and outside of DUD3. Because these measurements were recorded by a third party, and no post-manufacturing calibration was undertaken on the sensors, the dataset from DUD3 has only been used for periods when no other data is available. Only temperature data is presented in this report. Summer-only data from DUD1 and DUD2 were previously presented in Smith et al. (2008) (where they were denoted M1 and P1, respectively), and were discussed by McChesney (2009).

2.2 Modelling

The aim of the modelling work was to develop a tool that could be used to assess the potential of using roof spaces as a heat source in domestic dwellings, and to examine how this may change with location throughout New Zealand.

A model was developed using energy balance principles to estimate the roof space air temperature of a New Zealand house, based on the physical properties (size, orientation, construction) of house DUD1 (and DUD3 for some simulations). Construction elements used in the modelled house such as the pitched corrugated iron roof and timber framing are common in many New Zealand houses. MATLAB, a high-level technical computing language, was used to implement and run this model. The only input data required to operate the model were standard weather station variables (ambient air temperature, humidity, wind velocity, wind direction, air pressure, and global irradiance data), which are available for many locations around New Zealand (National Institute of Water and Atmospheric Research, 2010), and basic properties of each house (e.g. roof material, window sizes, house orientation). For Dunedin, data from the Energy Studies Weather Station at the University of Otago (2010) was used as this was the closest weather station to the monitored houses.

Applying physical principles from the scientific literature on heat and mass transfer, four interdependent equations were developed that described, (i) how the roof surface temperature changed with time, (ii) how the air temperature in the roof-space changed with time, (iii) how the air temperature in the occupied rooms changed with time, and (iv) the effect of any thermal mass at reducing temperature swings within the house. All four equations only require input data from the weather station and certain parameters particular to the house investigated. Solving these equations simultaneously allowed determination of the amount of heat that is transferred to and from the roof space air. A schematic diagram for the energy flows in and out of the modelled house is shown in Figure 1.

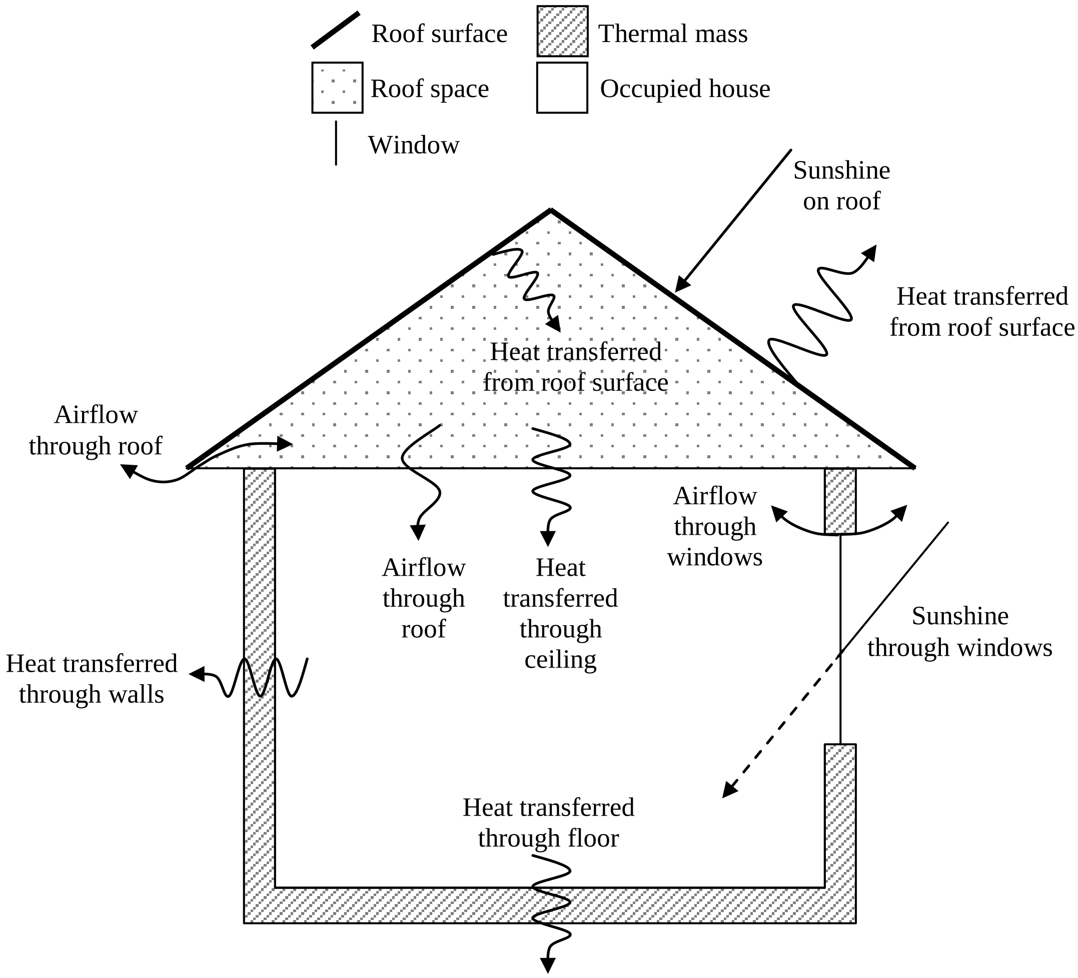

Figure 1. Schematic diagram for the energy flows through the modelled house

The primary controlling factors in the model are the amount of incoming sunshine, the outdoor temperature, and the level of air leaking or blowing into the roof cavity. The formal terms for these factors are incident solar radiation, ambient air temperature, and the air infiltration rate, respectively.

Full details of the equations and assumptions used in this research are available in Fitzgerald et al. (2011). Once published, the contents of this international peer-reviewed journal article will be accessible to the public through the University of Otago Energy Studies website (http://www.physics.otago.ac.nz/nx/eman/housing-research-downloads.html).

3 Results

The developed model takes standard weather station variables as input data, as well as specific physical properties of the investigated house (DUD1 or DUD3), to predict the temperatures in the roof space and living areas of the house. The model output was compared with three monitored houses located in Dunedin, New Zealand, as a means of validation. The monitored house DUD1 was then theoretically transplanted to other main centres around New Zealand within the model to assess variability throughout the country. The same house parameters were used for all locations so that all other factors stayed the same and any observed differences could be solely attributed to the difference in location. Both the heating and cooling potential of roof space air were assessed to calculate the maximum thermal benefits possible from pumping this air into occupied household areas.

3.1 Model Validation

The model was run for a representative period in summer, autumn, winter, and spring for each of the three monitored houses in Dunedin, New Zealand. Whenever possible, periods when the houses were unoccupied, or had low occupancy, were used, as this helped reduce the effect of human behaviour (e.g., opening windows, heating). The output data from the model were then compared with measured temperature data from the same period. Results are presented in Figures 2-5 for a five-day period in each of the respective seasons.

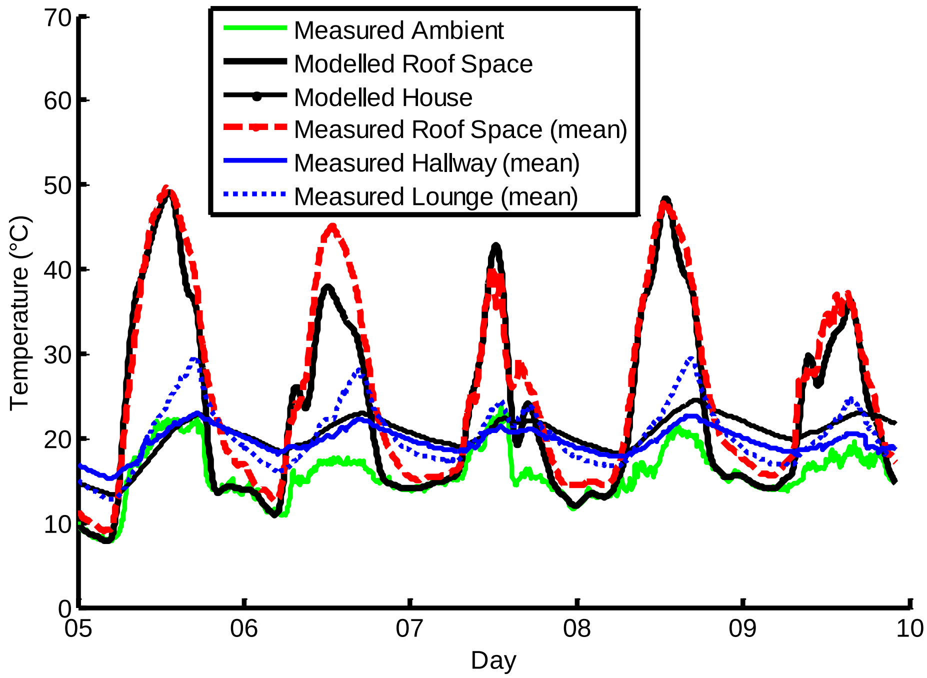

Figure 2. Model validation for 5-9 January 2008, representing a typical summer period for house DUD1.

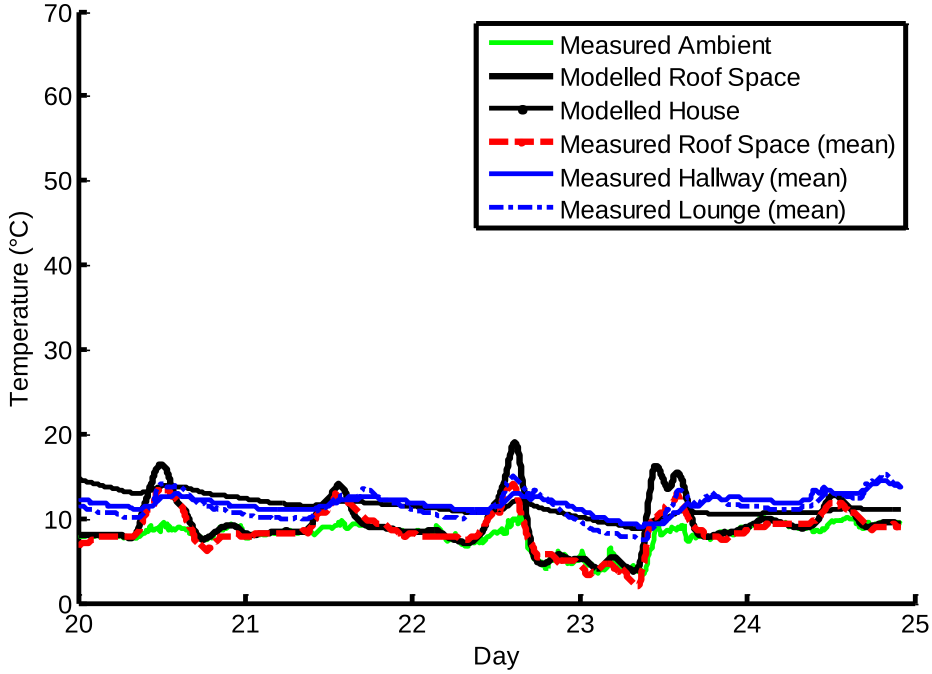

Figure 3. Model validation for 20–24 June 2009, representing a typical winter period for house DUD1.

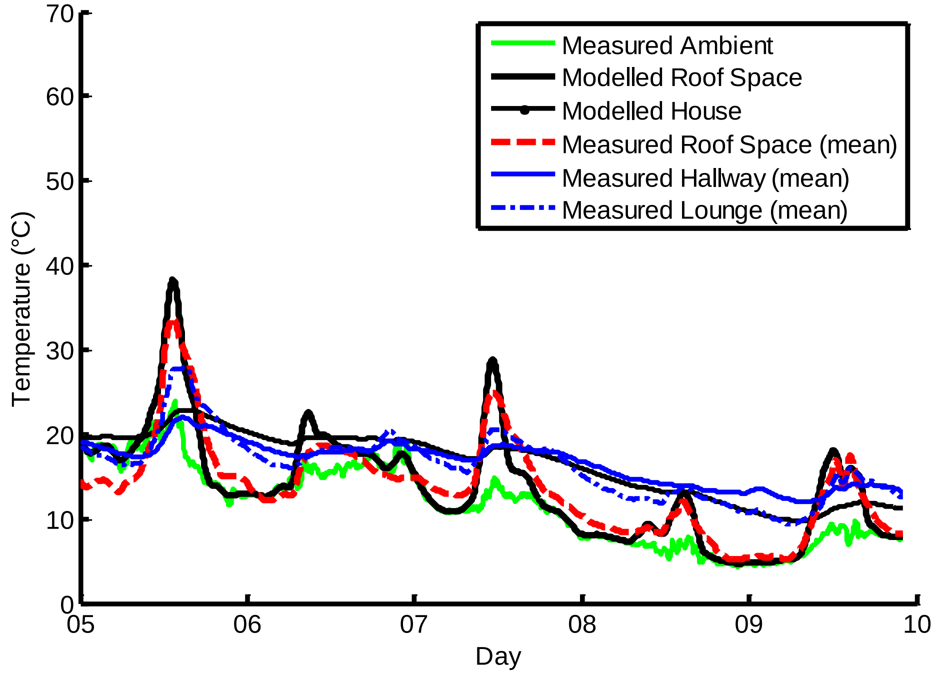

Figure 4. Model validation for 5– 9 April 2009, representing a typical autumn period for house DUD1.

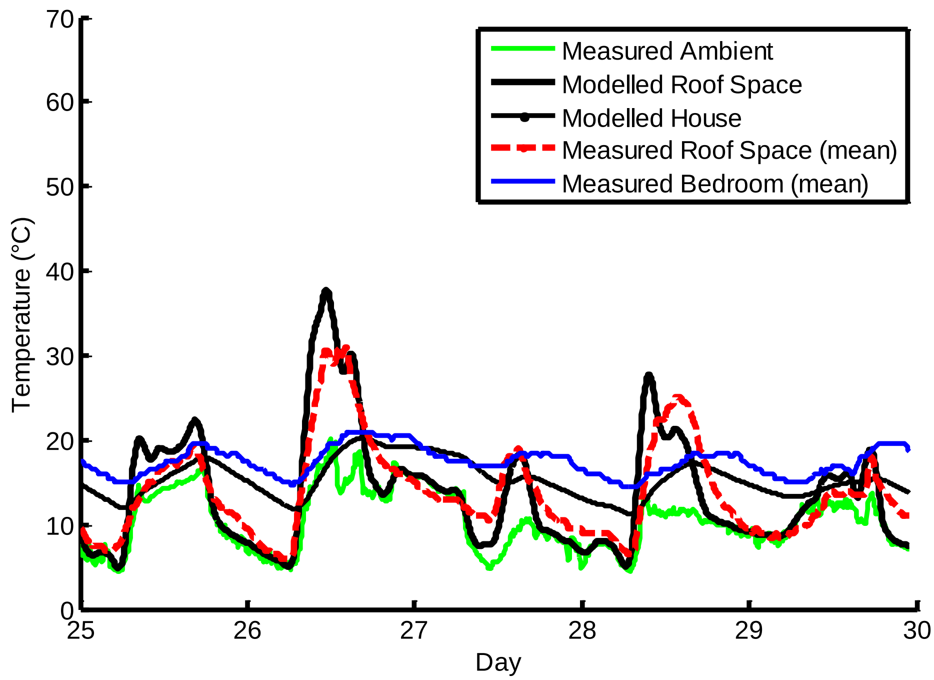

Figure 5. Model validation for 25 – 29 September 2008, representing a typical spring period for house DUD3.

The model is able to predict roof space temperatures relatively accurately for DUD1 during summer, autumn, and winter periods, as shown in Figures 2-4. Modelled roof space temperatures for DUD3 during spring periods (Figure 5) also follow the measured data relatively closely.

3.2 Main New Zealand Centres

To assess if certain regions within New Zealand were better suited to using roof space air as a source of heating and/or cooling, four main locations were modelled and compared to each other. The house parameters of DUD1 (size, orientation, construction) were applied to a location in Auckland (AKL), Wellington (WLG), and Christchurch (CHC). Weather station data was obtained from the National Institute of Water and Atmospheric Research website (2010) for each location. The modelled houses were set to the same latitude and longitude as the weather station in their region to avoid any local differences such as shading and/or shelter.

The timing of any possible heating and cooling benefits are taken into account so that they are only taken advantage of when they are required. For example: heating benefits are only calculated for times when the occupied rooms are below the desired inside temperature, but the roof space air is warmer than these occupied rooms. The opposite applies to any potential cooling benefits calculated with this model.

3.2.1 All seasons

The model was run in each of the four locations from 10-19 January, April, July, and October in 2008. This represents a characteristic period for summer, autumn, winter, and spring respectively. A desired temperature of 18°C was chosen as a reference as this is recommended by the World Health Organization (1985) as a healthy indoor air temperature. The results are shown below for comparison in Table 1. The potential benefits presented in Table 1 have been calculated assuming that the air flow from the roof space to the occupied rooms will be stopped when the roof space air is colder than 18 degrees (in case (a), heating) and when the roof space is hotter than 18 degrees (in case (b), cooling). This is not the case for most current positive pressure ventilation systems on the market, which continue to blow air from the roof space, although at a reduced flow rate, in those circumstances.

Table 1. Average heating (*a*) and cooling (*b*) benefits in kW (kilowatts) to occupied rooms with a desired internal temperature of 18°C. Model has been run 10 – 19 of January, April, July, and October in 2008. Note: these potential benefits have been calculated assuming that the air flow from the roof space to the occupied rooms will be stopped when the roof space air is colder than 18 degrees (in case (a), heating) and when the roof space is hotter than 18 degrees (in case (b), cooling).

a

	January	April	July	October
DUD	0.07	0.24	0.26	0.52
CHC	0.01	0.19	0.34	0.30
WLG	0.02	0.06	0.18	0.20
AKL	0	0.09	0.31	0.19

b

	January	April	July	October
DUD	0.92	0.19	0	0.23
CHC	1.0	0.33	0	0.67
WLG	0.63	0.44	0	0.40
AKL	0.93	0.60	0	0.55

Table 1 shows that in general, the heating potential of roof space air during all seasons increases as you travel south through the main centres in New Zealand. The opposite is the case for cooling whereby any benefits are generally more prominent in the northern centres. This is most likely due to the fact that southern homes require more heating and northern homes require more cooling as they often spend a greater proportion of the time below and above the desired temperature respectively. This means that there is a greater amount of time that the thermal benefits from the roof space air can be taken advantage of resulting in more energy benefits.

Table 1(*a*) shows that most of the potential heating benefits occur in winter (July) and spring (October) when the roof space air is warmer than the occupied room air, but the living areas are still colder than the desired temperature for thermal comfort. Summer provides the least potential heating benefits since when the roof cavity is warmer than the occupied rooms, those rooms are often already above the desired temperature. At such times, the rooms therefore require cooling, which is not available using roof space air. This situation can be visually seen in Figure 2 where the roof space air reaches extreme temperatures of up to 50°C, but these extremes occurred at times when the living areas were also at temperatures well above the desired level of 18°C.

The opposite effect is observed for the cooling potential of roof space air as shown by Table 1(*b*). Table 1(*b*) quantifies the amount of excess heat which can effectively be continuously displaced from the house by pumping cooler roof space air into the living areas. Summertime represents the greatest potential cooling benefits from pumping roof space air down into the occupied rooms, followed then by the shoulder seasons. Winter periods offered no potential cooling benefit, as the living areas never exceed the desired temperature and therefore never require cooling, as shown visually by Figure 3.

The magnitude of any potential benefits shown in Table 1 however, is not sufficient to significantly alter the indoor air temperature on average. Throughout the four representative seasonal periods in 2008, the maximum heating potential was only about 0.52 kW, which is approximately equivalent to the heat output from five 100 watt light bulbs. The maximum cooling potential of pumping cool air down from the roof cavity was around 1 kW.

As shown by Figures 2-5 and Table 1, the majority of the time, pumping roof space air into occupied rooms would provide little heating or cooling benefit. In fact, this would often act to actually drive the internal temperature further away from the desired level rather than closer towards it.

4 Recommendations

4.1 Policy

Based on the modelling work detailed in this report, it is recommended that existing positive pressure mechanical ventilation systems should not be promoted and marketed on their heating and/or cooling potential.

4.2 Research

There are many aspects of ventilation that were not taken into account in the undertaken research. Although a thorough analysis of using roof space air as a source of thermal benefits to a household has been provided in this report, there is still a significant lack of independent research around other aspects of ventilation systems. Indoor humidity levels were not analysed in this research, and should be the next step for any future research into positive pressure mechanical ventilation systems. Indoor humidity levels not only affect when condensation will form on colder objects, but it also affects the heat capacity of air, which changes the amount of energy required to heat a home. In general, the more moisture contained within the air, the harder it will be to heat. Many claims have been made about the ability of positive pressure mechanical ventilation systems to help reduce condensation levels in homes, although there has been little independent research to test these statements. It is known (Bassett, 1997) that supply-only ventilation systems work as dilution ventilators. This means they have less effective moisture capture efficiency than a ventilation system that extracts moisture directly from bathrooms and the kitchen. Both methods would result in a reduction of condensation but via completely different methods which would have flow-on implications for several energy and health related factors. After the University of Otago research was carried out and the paper Fitzgerald et al. (2011) submitted, two reports on preliminary research by other organisations into installed positive pressure ventilation systems were released: see Pollard and McNeil (2010) and Boulic et al. (2010).

The ability for mechanical ventilation systems to remove contaminants from the internal environment and introduce fresh air will also need further research. Many of these contaminants can be investigated together with the indoor moisture levels, although this may only become clear as future research progresses.

5 Conclusions

This report has described research undertaken at the University of Otago Physics Department into the potential heating and cooling benefits of roof space air, as used by positive pressure mechanical ventilation systems. A mathematical model was developed to predict the temperatures of the air in a roof space and living areas of a household based on standard weather station input variables. The model was validated against measured temperature data from three houses located in Dunedin, New Zealand. Simulations were run for the same house in Auckland, Wellington, Christchurch and Dunedin to compare how location changes the ability of roof space air to be used as a heat source.

Although heating and cooling benefits are possible at certain times from pumping roof space air into living areas, they are not sufficient to alter the indoor air temperature significantly. Throughout the four representative seasonal periods in 2008, the maximum heating potential was only about 0.52 kW, which is approximately equivalent to the heat output from five 100 watt light bulbs. The maximum cooling potential of pumping cool air down from the roof cavity was around 1 kW. Pumping roof space air into occupied rooms continuously would provide little heating or cooling benefit on average. In fact, this would often act to actually drive the internal temperature further away from the desired level rather than closer towards it.

More research is required to investigate other aspects of ventilation systems such as their ability to reduce moisture and other contaminants. Other potential concerns with interchanging roof and living space air, such as fire/smoke hazards and New Zealand building code requirements, have also not been taken into consideration in the current research. However, it is recommended that positive pressure mechanical ventilation systems are not installed in New Zealand houses for any potential heating or cooling benefits that they may provide.

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