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Edited by

Marc Aurel Schnabel

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Field Study of Auckland Housing Winter Indoor Health Conditions Associated with Insulation, Heating and Energy

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Abstract: Common problems of winter indoor micro-climatic conditions of Auckland houses are low air temperature and high relative humidity. Winter indoor air temperature and relative humidity are mainly impacted by house design with different insulation in their envelopes, different space heating methods and how much energy is used for space heating. The three Auckland houses, with different insulation and glazing in their envelopes and different space heating methods (temporary heating and central heating), were selected for field studies of winter indoor microclimatic conditions. According to the field study data and energy data, the study identifies differences in indoor thermal and health conditions of local houses with different R-value building envelopes, investigates what type of space heating is suitable and how much space heating energy is needed to achieve the guidelines for indoor thermal comfort and healthy conditions for a local lightweight timber frame construction house with sufficient insulation and double glazed windows. To compare and identify differences of energy consumption between the house using central heating and the local houses using different temporary space heating, this study randomly collected the energy data of 131 Auckland sample houses using different temporary heating methods, with or without sufficient insulation and double glazed windows.

Keywords: Housing Energy; Indoor health; insulation; space heating.

1. Introduction

Auckland's climate is temperate, with summers being comfortable, warm and dry, and winters being mild and wet, which requires only limited winter heating and does not require summer cooling. Auckland has around 1,150 heating degree days (the base temperature used is 18 ºC) [NZMS, 1978]. Previous studies show that indoor air temperatures of New Zealand homes are quite low compared with the guidelines for thermal comfort and healthy conditions during winter time [Boulic *et al.*, 2008; Lloyd *et al.*, 2008]. Only about 5% New Zealand houses use a central heating system [French *et al.*, 2007]. The World Health Organisation (WHO) recommends a healthy minimum indoor temperature of 18°C for houses; and 20-21ºC for more vulnerable occupants, such as older people and young children [WHO, 1987].

High winter indoor relatwive humidity is a major issue for Auckland housing indoor health conditions. New Zealand has some of the highest levels of house dust mite allergens in the world [Siebers, 2006]. Visible mould growth on indoor surfaces is a common problem in over 30% of New Zealand houses [Howden-Chapman *et al.*, 2005]. The abundance of two major causes of allergy, mites and mould in New Zealand housing, increase proportionately with average indoor relative humidity. One option to prevent mould growth on indoor surfaces is to control the indoor humidity level under the threshold (80%) of mould gemmation. If the mould spores never start gemmation then mould will not grow on indoor surfaces [Su, 2006; ASHRAE, 1993]. According to international and national standards, the indoor relative humidity should be lower than 60% for indoor air quality [ASHRAE, 1992; ASHRAE, 1993; ASHRAE, 2001; SNZ, 1990; DBH, 2001]. Most of the health effects such as bacteria, viruses, fungi, mites, etc. have increases associate with very high indoor relative humidity. Maintaining indoor relative humidity between 40% and 60% can minimize the indirect health effects [Arundel, 1986] (see Figure 1).

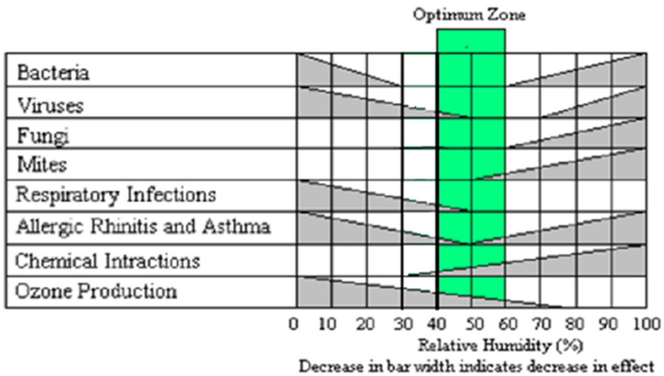

Figure 2: Health effects and indoor relative humidity (Source: Arundel, et al. 1986)

Since 1978, continuously increasing R-value of building envelope of Auckland houses in accordance with the updated building standards mainly focus on improving energy efficiency [SNZ, 1977; BIA, 1992]. Houses without sufficient insulation are not energy efficient and it is expensive to heat up indoor space. Government funded Warm up New Zealand: Healthy Homes projects, administrated by the Energy Efficiency Conservation Authority (EECA), provide free ceiling and underfloor insulation to low-income households with people who have health needs related to cold and damp housing. Previous studies of retrofitting New Zealand housing projects show that increased insulation in the building envelopes can only increase 1°C or less than 1°C of indoor mean air temperatures [Isaacs, 2006; Lloyd, 2008]. Increasing insulation without tackling the lack of space heating is not a good idea [Gustafsson, 2000]. The study investigates what type of space heating is suitable for the local house with lightweight timber frame construction and identifies how much space heating energy is needed for the local houses to achieve the guideline of winter indoor thermal comfort and healthy conditions [WHO, 1987; Arundel, 1986].

New Zealand housing energy efficiency should include insulating the complete building fabric and using energy efficient space heating [Verebeek, 2005]. The New Zealand government continuously publishes New Zealand's energy strategy and policy every 5 years for improving New Zealander's health related to living conditions, saving housing energy and reducing greenhouse gas emissions. Inadequate insulation combined with ineffective space and water heating systems are found in many New Zealand homes [MED, 2011; EECA, 2011]. If a household spends more than 10% of its income on heating merely to maintain adequate warmth it is deemed to be in "fuel poverty" [Boardman, 1991; Clinch and Healy, 2001]. It is thought that approximately 25% of New Zealand homes are living in fuel poverty [Howden-Chapman *et al.*, 2012]. Recent studies related to New Zealand fuel poverty issues are based on existing New Zealand designs, space heating methods, hot water systems and housing energy [O'Sullivan *et al.*; Lawson *et al.*, 2015]. The Household Energy End-use Project (HEEP) found that the main use of energy across all types of fuel in a New Zealand household was for space (34%) and water (29%) heating. New Zealand houses have the highest percentage (77%) of electric hot water systems in the Western world. It is anticipated that a move to mains pressure gas hot water systems would significantly affect both energy and water usage [Isaacs *et al.*, 2006].

2. Methodology

To investigate winter indoor thermal comfort and healthy conditions of Auckland houses with different R-values of building envelopes and different space heating methods (temporary and permeant heating), three Auckland houses with lightweight timber frame construction were selected for the field studies of winter indoor micro-climatic conditions. House 1 was built in 2000 (R-values for Roof: 1.9, Wall: 1.5, Floor: 1.3, Single Glazing: 0.13). House 1 had 2 occupants and used an electronic cylinder hot water system and an electronic oil heater in the master bedroom only for the evening time during the field study. House 2 was built in 2012 (R-values for Roof: 2.9, Wall: 1.9, Floor: 1.3, Double Glazing: 0.26). House 2 had 2 occupants and used a gas instant hot water system but did not use any space heating during the field study, although there is a heat pump. House 3 was built in 2012 (R-values for Roof: 2.9, Wall: 1.9, Floor: 1.3, Double Glazing: 0.26). House 3 had 2 occupants and used a gas instant hot water system and a gas central heating system during the field study. Indoor air temperature of House 3 was set at 20°C in the downstairs living room during the field study. Monthly electricity and gas consumption data for the three houses were collected for this study. The air temperature and relative humidity adjacent to floors and ceilings of indoor spaces in three houses and under shaded outdoor space were continuously measured at 5-minute intervals 24 hours a day for about 56 days during the winter months from June to August 2014 (16382 air temperature measurements for each data logger or each test point), by Lascar Humidity Data Logger.

The study not only identifies the difference of indoor mean air temperature and relative humidity of the sample houses but also difference of percentage of winter time, when indoor air temperature and relative humidity meets or does not meet the guidelines of thermal comfort and healthy conditions. To compare differences in the 24-hour mean indoor air temperature in winter and investigate the 24-hour mean variations of indoor air temperatures in winter of the three houses all field study data of indoor air temperatures (16382 air temperature measurements for each data logger or each test point) of the three houses in winter have been converted into the winter hourly mean air temperature (about 682 air temperature measurements within a particular hour in winter are averaged for the hourly mean air temperature). Monthly energy data and building plans of 70 Auckland sample houses built after 2007 with sufficient insulation and double glazing windows and 61 Auckland sample houses built after 2000 with insufficient insulation and single glazing windows were randomly collected for this study.

3. Results and Discussion

3.1. Winter indoor thermal and health conditions of the three houses

Although House 1 used an electronic heater in the master bedroom during the field study, indoor mean air temperature of House 2 is 1.1°C higher than House 1 and the percentage of winter time in House 2, when indoor air temperatures are higher than or equate to 18°C, is 17.6% higher than House 1 (see Table 1 and Table 2). Mean relative humidity of House 2 is 4.9% lower than House 1 and the percentage of winter time in House 2, when indoor relative humidity is between 40% and 60%, is 19.6% higher than House 1. Although upgrading insulation and using double glazing windows can significantly increase the percentage of winter time, when indoor air temperatures and relative humidity can meet the guidelines of health conditions, there is still 78.5% of winter time when indoor air temperatures are lower than 18°C and 71.6% of winter time when indoor relative humidity is higher than 60% compared with House 3. An Auckland house with sufficient insulation and double glazing windows needs space heating_to achieve winter indoor thermal comfort and health conditions (18°C for the minimum indoor temperature and 40%-60% for indoor relative humidity).

Table 1 Percentages of winter time and mean indoor air temperature ranges of the three houses

	≥16°C	≥18°C	≥20°C	≥22°C	≥24°C	≥26°C	Mean	Max.	Min.	Fluctuation
House 1	35.3%	3.9%	0%	0%	0%	0%	15.5	19.8	11.4	8.4
House 2	61.0%	21.5%	2.5%	0.01%	0%	0%	16.6	22.1	11.2	10.9
House 3	100%	100%	98.70%	44.50%	1.30%	0.01%	21.9	27.3	18.8	8.5

Table 2 Percentages of winter time and mean relative humidity ranges of the three houses

	≥40%	≥50%	≥60%	≥70%	≥80%	40% to 60%	Mean	Max.	Min.	Fluctuation
House 1	100%	100%	92.2%	37.6%	1.0%	8.8%	68.3%	82.9%	54.3%	28.6%
House 2	100%	100%	71.60%	11.90%	0%	28.4%	63.4%	81.0%	51.1%	29.9%
House 3	100%	28.8%	0.0%	0.0%	0%	100%	48.1%	56.7%	38.5%	18.2%

3.2. How much the space energy is needed to achieve indoor health conditions?

House 2 and House 3 have the same R-value in their envelopes. With a central heating system, House 3 has 100% of winter time when indoor air temperatures are higher 18 °C and indoor relative humidity is between 40% to 60% for all indoor spaces (see Table 1 and Table 2). Table 3 shows energy data of the three houses. As space heating energy is closely related to the volume of indoor space, the study uses daily mean energy consumption per cubic metre of indoor space (kWh/m^{3}day) as a basic energy unit. House 3 used gas for the gas central heating system, gas instant hot water system and cooking during the space heating months. House 3 used gas for the gas instant hot water system and cooking during the no space heating months. The difference of daily mean gas usage per cubic metre of indoor space between the space heating months (May to September) and the no space heating months of House 3 can mainly represent its space heating energy. The difference of daily mean gas usage per cubic metre of indoor space between the space heating months and the no space heating months of House 3 is 0.0689 kWh/m^{3}day, which can mainly represent the space heating energy needed to achieve the guideline of indoor thermal comfort and health conditions (for 20°C as the minimum indoor air temperature) of a local house with lightweight timber frame construction with sufficient insulation in its envelope according to the current building code.

During no space heating months, daily mean energy of House 1 (0.03564 kWh/m^{3}day) with an electronic hot water cylinder is significantly higher than house 2 (0.01630 kWh/m^{3}day) and House 3 (0.02350 kWh/m^{3}day) with gas instant hot water systems. During no heating month energy used for hot water is the major part of energy consumption. House 1 with an electronic cylinder hot water system could use more energy for hot water than House 2 and House 3 using gas instant hot water system. There is a short time for occupants to use hot water for a shower or other purposes during the 24-hour day. Current hot water cylinders continuously heat water and maintain water temperature at a temperature of 24 hours a day whether hot water is needed or not. During the winter night when occupants do not use hot water and internal air temperature is very low, especially for those houses without sufficient insulation, heat loss from a cylinder to the cold internal space can consume some extra energy for maintaining the water temperature.

Table 3 Energy data (kWh/m^{3}day) of the three houses

	House 1	House 2	House 3	House 2	House 3
	Total energy Electricity only	Total energy Electricity and gas	Total energy Electricity and gas	Gas only	Gas only
Annual	0.04878	0.01919	0.05286	0.00871	0.04593
Heating months	0.06699	0.02319	0.09354	0.01162	0.08595
Other months	0.03564	0.01630	0.02350	0.00661	0.01705
Difference	0.03135	0.00689	0.07004	0.00501	0.06890

3.3. Discussion of local housing energy consumption

Mean annual daily energy consumption (0.06367 kWh/m^{3}day) of the 61 sample houses with insufficient insulation and single glazed windows is higher than the 70 sample houses with sufficient insulation and double glazed windows (0.05848 kWh/m^{3}day) (see Table 4). The houses with higher R-value building envelope (higher insufficient insulation and double glazing window) are more energy efficient. The difference of daily mean energy usage per cubic metre of indoor space between heating and no heating months of House 3 (0.07004 kWh/m^{3}day) is significantly higher than the 61 houses (0.03151 kWh/m^{3}day) and the 70 sample houses (0.02588 kWh/m^{3}day). The Auckland sample houses with temporary heating methods use less space heating energy than House 3. Generally, Auckland houses with temporary space heating do not heat up the whole house and only heat up some indoor spaces, such as living room or bedroom, mainly for winter evenings, nights and early mornings. For the no space heating months, daily mean energy consumption of the 61 sample houses (0.05046 kWh/m^{3}day) and the 70 sample houses (0.04763 kWh/m^{3}day) are significantly higher than House 3 (0.02350 kWh/m^{3}day). 67% of the 61 sample house and 66% of the 70 sample house use electric hot water cylinders. As water heating is a major part of energy consumption during no space heating months, the energy used for hot water in the 131 Auckland sample houses could be more than for House 3. A further study should focus on what type of hot water system is energy efficiency for the local houses.

Table 4 Energy data (kWh/m^{3}day) of house 3 and the 131 Auckland sample houses

	House 3	70 houses with double glazing			61 houses with single glazing		
	Total energy	Mean	Max	Min	Mean	Max	Min
Annual	0.05286	0.05848	0.16345	0.02004	0.06367	0.14512	0.01570
Space heating months	0.09354	0.07351	0.19856	0.02177	0.08197	0.20669	0.02007
No heating months	0.02350	0.04763	0.13812	0.01833	0.05046	0.11741	0.01254
Difference	0.07004	0.02588	0.11496	0.00235	0.03151	0.12975	0.00478

3.4. Major issues for local house thermal design

3.4.1. Low air temperature and high relative humidity in southern downstairs bedrooms

Winter indoor mean air temperatures of southern downstairs bedrooms are significantly lower than other spaces in both House 1 and House 2 with different R-value in their building envelopes (see Table 5), which can result in higher indoor relative humidity (Table 6). House 2 having higher R-value insulation in its envelope does not efficiently improve indoor thermal and health conditions of the southern downstairs bedroom. The southern downstairs indoor space is in cold side of house without direct sun light. Southern bedrooms are commonly smaller than the northern bedrooms and the other spaces; the floor area of the downstairs southern bedroom (10.3m^2) of House 2 is smaller than the master bedroom (17.7m^2) and the open living space (68.2m^2). A southern bedroom with a smaller floor area could potentially result in big ratios of external wall area to indoor space volume or window area to floor of that room. The ratio of the external wall area to indoor space volume of the downstairs southern bedroom (0.65) is higher than the open living space (0.4) and master bedroom (0.49). Although the ratio of northern window area to northern wall (0.2) of House 2 is higher than southern window area to southern wall area, the ratio of window area to indoor space volume of the southern downstairs bedroom (0.09) is higher than the northern downstairs open living space (0.06). Windows are commonly a weak part of the building envelope for thermal resistance, even double glazed windows, compared with wall and roof with sufficient insulation. Negative impact of a big ratio of window to floor could overrule or degrade the positive impact of higher insulation levels and double glazed windows on indoor thermal comfort and health conditions of a southern indoor space conditions. A further study can focus on adding more insulation in the southern wall and limiting the ratio of window area to indoor space volume of the southern indoor space for improving indoor health conditions of southern indoor spaces.

Table 5 Percentages of winter time and air temperature ranges of different indoor spaces

	Location	≥16°C	≥18°C	≥20°C	≥22°C	≥24°C	≥26°C	Mean
House 1	Living	34.7%	4.6%	0.1%	0%	0%	0%	15.5
	Downstairs bedroom	11.2%	0%	0%	0%	0%	0%	14.2
	Upstairs master bedroom	69.2%	32.7%	6.7%	0.1%	0%	0%	16.9
	Corridor	34.0%	2.9%	0%	0%	0%	0%	15.3
House 2	Living	78.7%	21.8%	1.0%	0%	0%	0%	16.8
	Downstairs bedroom	28.3%	4.9%	0%	0%	0%	0%	14.8
	Upstairs master bedroom	71.1%	44.9%	18.7%	6.4%	0.9%	0.1%	17.9
	Corridor	76.2%	30.7%	4.0%	0.2%	0%	0%	17.0
House 3	Downstairs	100%	100%	100%	68.2%	1.1%	0%	22.2
	Upstairs master bedroom	100%	99.9%	98.6%	62.5%	13.3%	1.0%	22.6
	Upstairs south bedroom	100%	100%	82.5%	19.4%	0.1%	0%	20.9
	Corridor	100%	100%	84.7%	12.3%	0.1%	0%	20.8

Outdoor	1.70%	0%	0%	0%	0%	0%	10.4

Table 6 Percentages of winter time and relative humidity ranges of different indoor spaces

	Indoor spaces	≥40%	≥50%	≥60%	≥70%	≥80%	40% - 60%	Mean
House 1	Living	100%	100%	90.8%	34.7%	0%	9.2%	67.7%
	Downstairs bedroom	100%	100%	100%	71.4%	13.4%	0%	73.4%
	Upstairs master bedroom	100%	100%	69.7%	24.6%	0%	30.3%	64.3%
	Corridor	100%	100%	90.4%	35.8%	1.5%	9.6%	67.9%
House 2	Living	100%	99.4%	69.2%	11.8%	0%	30.8%	62.8%
	Downstairs bedroom	100%	100%	95.7%	41.4%	2.5%	4.3%	68.6%
	Upstairs master bedroom	100%	97.5%	58.6%	8.0%	0%	41.4%	61.1%
	Corridor mean	100%	100%	69.7%	10.8%	0.04%	30.3%	63%
House 3	Downstairs Living	100%	40.6%	0%	0%	0%	100%	49.1%
	Upstairs master bedroom	99.8%	24.3%	0%	0%	0%	100%	47.5%
	Upstairs south bedroom	100%	66.8%	0%	0%	0%	100%	51.6%
	Corridor	100%	24.3%	0%	0%	0%	100%	47.6%
Outdoor	Outdoor	100%	99.9%	97.4%	86.8%	68.4%	2.6%	85%

3.4.2. Large fluctuations of indoor air temperature and discussion of space heating method

Fluctuations in indoor air temperatures and relative humidity of House 1 and House 2 are both large (see Figure 1 and Figure 2). Large fluctuations of winter indoor air temperature can result large fluctuations of indoor relative humidity (Figure 2), which can negatively impact winter indoor health conditions. In common with most Auckland houses, House 1 and House 2 are lightweight timber frame construction with internal insulation and external cladding, of break veneer in this instance. Wall insulation materials are located at the internal surface of the wall as thermal designs of House 1 and House 2 are for temporary heating, not for permanent heating. As the internal surface of the wall does not have thermal mass, the space can be heated quickly, rather than heating the building envelope first and then heating the space. For this type of lightweight building envelope without sufficient thermal mass on the internal surface of the wall, the indoor space air temperature is heated up quickly by solar radiation and rising outdoor air temperatures during winter daytime and also cooled down quickly during winter night time. Figure 3 shows winter indoor hourly mean air temperatures of House 1, House 2 and House 3. Indoor minimum air temperatures in winter of House 1 and House 2 occur during early morning. Minimum winter indoor hourly mean air temperatures of House 1 (14.1°C) and House 2 (14.8°C) occur at 6:45 to 8:30 for House 1 and at 7:45 to 8:05 for House 2. Large fluctuations in indoor air temperatures can result in very low indoor air temperatures during early morning and night time in winter, negatively impacting indoor thermal comfort and health conditions and costing more in energy for space heating to achieve the indoor thermal and health conditions.

Reducing the fluctuation of winter indoor air temperature can improve indoor health conditions and housing energy efficiency. Suitable space heating can not only raise indoor mean air temperature but also fill variable gaps or differences between indoor air temperature and the minimum indoor air temperature required for thermal comfort and healthy conditions during the 24 hours of winter time. Space heating needs to be automatically controlled to achieve and maintain winter indoor thermal comfort and health conditions of a local house with lightweight timber frame construction.

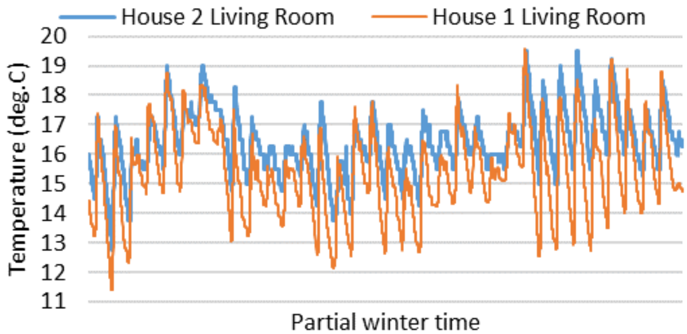

Figure 1: Partial winter air temperatures in the living rooms of House 1 and House 2

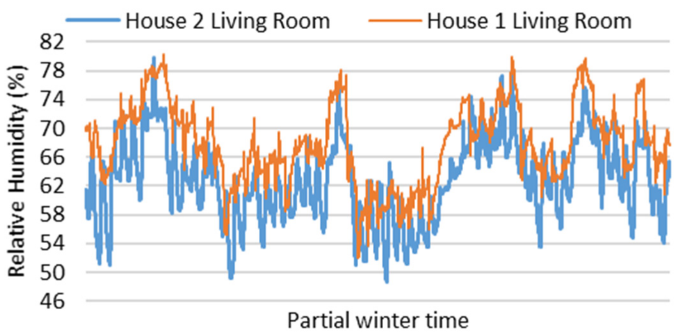

Figure 2: Partial winter relative humidity in the living rooms of House 1 and House 2

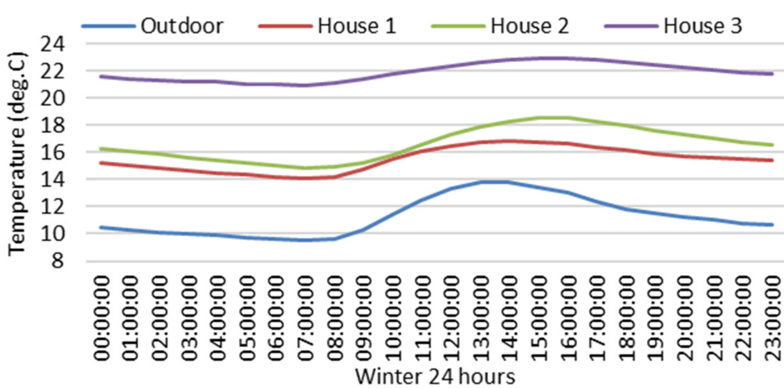

Figure 3: Winter indoor and outdoor hourly mean air temperature of the three houses

4. Conclusion

According the field study data of House 1 and House 2, increasing R-value of building envelope from 1.9 for roof, 1.5 for wall, 1.3 for floor and 0.13 for glazing, as required by the New Zealand building standards in 1996, to the 2009 requirements of 2.9 for roof, 1.9 for wall, 1.3 for floor and 0.26 for glazing can increase 17.6% of winter time, when indoor air temperatures are higher than or equate to 18°C (the minimum indoor air temperature required for health conditions) and 19.6% of winter time, when indoor relative humidity is between 40% and 60% (minimizing indirect health effects). Although sufficient insulation and double glazed windows significantly improves indoor thermal and health conditions of House 2 compared with House 1, 78.5% of winter time the indoor air temperatures are lower than 18°C and 71.6% of winter time when indoor relative humidity is higher than 60%. Auckland houses with sufficient insulation and double glazing windows need space heating to achieve winter indoor thermal comfort and healthy conditions.

An Auckland lightweight timber frame construction house has large fluctuations of indoor air temperatures during the 24 hours of winter time. To achieve indoor thermal comfort and healthy conditions, suitable space heating can not only raise indoor mean air temperature but also fill variable gaps or differences between indoor air temperature and the minimum air temperature required for thermal comfort and healthy conditions during the 24 hours of winter time. Space heating has to be controlled according to different needs during 24 hours of winter time, which can not only make indoor thermal comfort and healthy conditions stable, but also save heating energy. Based on House 3 energy consumption data, 0.06890 kWh/m3day daily mean energy per cubic metre volume of indoor space is needed to achieve the guideline for thermal comfort and healthy conditions (for 20°C as the minimum indoor air temperature) in an Auckland house with sufficient insulation and double glazed windows in their lightweight timber frame construction envelopes. If indoor air temperature of House 3 is set at 18°C (not 20°C) in the downstairs living room during the winter, the space heating energy can be lower than 0.0689 kWh/m3day.

Based on energy data of the 131 Auckland sample houses with temporary space heating, the houses with higher R-value building envelope are more energy efficient. On average, the Auckland sample houses with temporary space heating use less space heating energy than the space energy needed to achieve the guidelines for thermal comfort and healthy conditions. For the no space heating months, daily mean energy consumption of the 131 Auckland sample houses is significantly higher than House 3 with gas instant hot water system. Over 66% of the Auckland sample house use electric hot water cylinders. During the no space heating months, the energy used for hot water becomes a major part of energy consumption. Increasing R-value of building envelope and increasing space heating energy for achieving indoor health conditions without tackling inefficient hot water system is not good idea for local housing energy efficiency. Reducing energy used for hot water and increasing space heating energy for occupants' health could be the future housing energy strategy for housing energy efficiency and reducing the fuel poverty of New Zealand households.

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