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A FIELD STUDY OF 'WIND-RAIN' HOUSE

Bin Su
School of Architecture, Unitec Institute of Technology, Auckland, New Zealand
bsu@unitec.ac.nz

ABSTRACT:
The first 'wind-rain' house, designed by nationally known architect Nigel Cook, was built in 1985 in New Zealand. The 'wind-rain' house is a house with a partially glazed roof mainly located in its centre or centre section. The glazed roof can be partially opened or closed. This is automatically controlled by a computer and provides natural ventilation to adjust indoor thermal comfort conditions. A number of 'wind-rain' house have been built without engineering analysis of their qualities. This is the first field study to investigate indoor thermal and health conditions and energy consumption in a 'wind-rain' house. It was carried out by the author during the Auckland winter of 2009. The study finds that the 'wind-rain' house has strong advantages in indoor thermal comfort under the winter conditions and better energy efficiency compared with conventional houses under the local climate. Improvement of the 'wind-rain' house design should focus on decreasing indoor relative humidity during the winter. The further study with more samples of 'wind-rain' houses is needed to develop detailed design guides for energy efficiency.
Conference Topic: The Earth/Desert/Green and Sustainable Buildings
Keywords: House, House Passive Design, Thermal Comfort, Indoor Health, Energy Efficiency

1. INTRODUCTION:

The 'wind-rain' house has big potential for the winter thermal comfort and energy efficiency. Since 1985, a number of 'wind-rain' houses have been built in New Zealand without any engineering analysis of their qualities of indoor thermal and health conditions. The 'wind-rain' houses have, however, been constantly monitored by the designer over the years to improve the 'wind-rain' house design mainly in response to owners' comments. This pilot study sets out to evaluate the thermal and health conditions, and the energy efficiency related to the Auckland climate according to the field study data. The 'wind-rain' house contains three sections. The north living section (one storey) contains the enclosed living room on west side and, open to the courtyard, the kitchen and dining room to the east. The middle section is the courtyard space itself with glass roof. The south sleeping section of two storeys has three bedrooms upstairs and, downstairs, two bedrooms with, in between, a large utility area open off the courtyard. In view of the studies' results it is noted that the three bedrooms at either end are the only rooms not adjacent to the courtyard. Figure 1-2 show the photo and plans of the 'wind-rain' house used for this study.

Fig.1 Photo of the ‘wind-rain’ house used for the field study

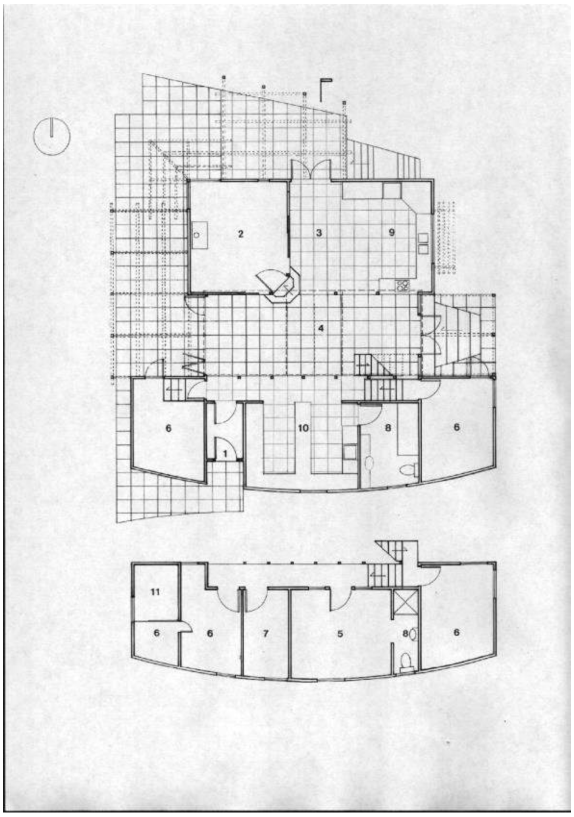

Fig.2 Plans of the ‘‘wind-rain’ house used for the field study

The partially glazed roof of the ‘wind-rain’ house however, while being a complete barrier to the wind and rain obtains the maximum direct sun light through the glass and traps solar energy within the open space beneath (the courtyard space). By direct radiation it heats walls and floor and by convection warms the spaces opening off it that are not immediately under the glass roof. Using solar power and photovoltaic the energy can be modified for use in the house or fed back into the public grid. In a conventional house with its insulated roof and walls most of the exterior blocks the suns energy and occupants then have to pay to import it back in the form of electricity, gas and oil with a huge net energy loss. Direct sun light can only get into the house through windows and glazed doors. Correct orientation is very important to ensure the living space windows catch the strong northern sun. The ‘wind-rain’ house, however, can face any direction and the rooms can be arranged freely in the most appropriate relationships without loss of energy because the sun light is coming in over the top of them into the protected centre space. So the ‘wind-rain’ house always has the equivalent of two north walls – one in the protected space inside and a conventional one outside. The 'wind-rain' house has two type of indoor spaces for the winter, the indoor space with the glass roof is for the winter daytime living while the indoor spaces with conventional roofs and walls are for winter night time living.

Auckland has a temperate climate with comfortable warn, dry summers and mild, wet winters. The winter temperatures are lower than the comfort zone (18 Cº to 28 Cº) but rarely below the 5 °C. An Auckland house normally does not need air conditioning for cooling during summer and only needs temporary heating during the winter. In Auckland, the design of a building should focus more on its indoor thermal conditions and thermal performance related to winter conditions for building energy efficiency (Su, 2004). The Auckland house passive design should focus on the winter thermal performance, which is not only for the winter thermal comfort but also for energy efficiency. The field study focuses on investigating the winter indoor thermal and health conditions of a 'wind-rain' house. Indoor and outdoor air temperature and relative humidity adjacent to floor and ceiling were continuously tested at 15-minute intervals, 24 hours a day during the winter months from June to August in 2009. The percentage of time related to different temperature ranges and the daily mean temperature profile of the winter months in different indoor spaces were used to evaluate indoor thermal and health conditions of this 'wind-rain' house to compare it with the conventional houses.

The difference between mean daily electricity usage in the winter months (June, July and August) and the other months of the year roughly represents the winter extra energy consumption, which mainly comprises space heating, extra energy for hot water and all appliances, which are impacted by the winter indoor thermal conditions of a house. A smaller difference between mean daily usage in winter months and the other months roughly represents the response of better indoor space thermal conditions in the winter climate (Su, 2006). A year's energy consumption data of the 'wind-rain' house was also collected and the daily mean energy consumption data per cubic volume of indoor spaces (kWh/m^3day) were calculated to evaluate building energy efficiency. This was compared with the mean energy consumption data of the mean winter extra energy of 200 conventional Auckland houses used for the previous study.

Auckland has a somewhat higher vapor pressure than other main New Zealand cities and the Auckland monthly mean relative humidity is very high especially during winter. The percentage of time related to different relative humidity ranges, the daily relative humidity profile and indoor mean temperature of the winter months in different indoor spaces are used to evaluate indoor health conditions of the 'wind-rain' house to compare with the conventional house. Figure 3 shows the optimum zone of indoor relative humidity and relationships between the indoor relative humidity and health effects. Indoor health effects such as bacteria, viruses, fungi, dust mites, respiratory infections, allergic rhinitis, asthma, chemical air pollutants, ozone production etc. are closely related to indoor relative humidity. The optimum zone of 30% - 60% relative humidity is in accordance with the international and national standards (ASHRAE Standard 62-2000, New Zealand Standard 4303-1990, ANSI/ASHRAE 55-1992, ASHRAE Handbook of Fundamentals 1993). This study compares indoor relative humidity between the 'wind-rain' house and a conventional house for evaluating indoor health conditions of the 'wind-rain' house.

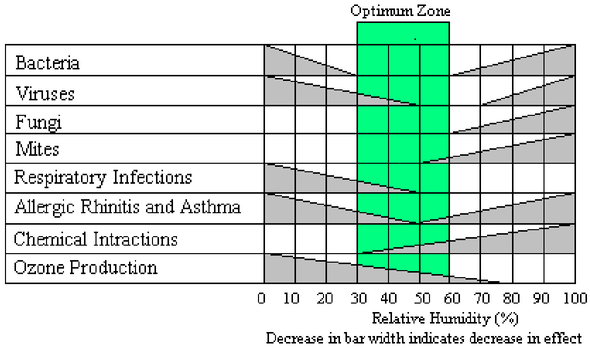

Fig.3 Relative humidity and health effects

2. INDOOR THERMAL CONDITIONS

Table 1 and table 2 show the percentages of the winter time related to different air temperature ranges for different indoor spaces of the 'wind-rain' house for this study and for a conventional house in Auckland (Su, 2006). The World Health Organization recommends 18°C as the minimum indoor temperature and 20-21ºC for more vulnerable occupants such as older people and young children. The current New Zealand Building Code does not have a requirement of minimum indoor air temperature for a house and only has a requirement of minimum indoor air temperature for more vulnerable occupants such as older people and young children. The 'wind-rain' house has much higher percentage of the winter time, when indoor temperatures reach 16°C, 18°C or 20°C, than the conventional house (see Table 1-2). The 'wind-rain' house has much better winter indoor thermal comfort condition than the conventional house.

Figure 4 shows hourly mean temperature profile of 24 hours during the winter months from June to August of the 'wind-rain' house. The lowest indoor temperatures occur at about 7-8am, the indoor spaces are initially warmed up by the sun at about 9am then indoor mean temperatures reach the highest temperature at about 2-3pm, after that peak temperature, indoor mean temperatures continuously decrease. After 6pm the decrease trends of indoor mean temperatures are interrupted by the heat from the cooking of the open kitchen or temporary heating during early night, then from the middle night indoor temperatures continuously decrease to the lowest indoor temperatures.

Table 5 shows mean temperatures of the daytime from 9am to 6pm and the percentage of day time when mean temperatures reach 16°C, 18°C and 20°C in the indoor spaces. The mean temperature from 9am to 6pm of the courtyard space is 19.2°C. The courtyard space is very comfortable indoor space for the daytime living. The mean temperatures of other indoor spaces are from 15.5 to 17.5°C, which meet the requirement for the minimum indoor temperature 16°C of New Zealand Standard. The mean temperature in the courtyard space is significant higher than other indoor spaces from 9am to 6pm and the peak mean temperature of the courtyard space is 3-5.5°C higher than other indoor spaces. The courtyard space can positively impact the indoor thermal comfort of the 'wind-rain' house. After the middle of the night, the mean temperature of the courtyard space is slightly lower than other indoor spaces but it has much better thermal condition than the outdoors during the winter night time. The mean temperature of the courtyard space is at least 3°C higher than the outdoor temperature during the winter night time (see Figure 4). Although the thermal resistance (R-value) of a single layer of glass (0.26 m^2 °C/W) is very low compared with walls (1-1.9 m^2 °C/W) and roofs (2.9-3.5 m^2 °C/W) insulated in accordance with the current standard, the glass roof of the 'wind-rain' house can still give the courtyard some protection from heat loss, and there is no air movement and wind-chill in the courtyard space during the winter night time.

Figure 5 shows mean air temperatures of the courtyard space and downstairs kitchen and living room. The mean air temperatures of the kitchen are higher than the living room during the daytime and lower than the living room during the night. Because there is no partition wall between the kitchen and the courtyard space, the courtyard space can have a more positive impact during the daytime but a negative impact during the night time on the indoor thermal condition of kitchen than it does on the living room with its partition wall. To open the doors of bedrooms to the courtyard space during the daytime should be good for both thermal comfort and health. How to design the partition walls adjacent to the courtyard space is also important for indoor thermal conditions of the 'wind-rain' house. To open partitions adjacent to the courtyard space during the daytime and close those partitions with good insulation during the night time is good for indoor thermal comfort during both daytime and night time.

Figure 6 shows mean air temperatures of the courtyard space of the 'wind-rain' house. Mean air temperatures close to the floor, the middle and the ceiling of the courtyard space are 15.7°C, 19.3°C and 22.9°C. The mean air temperature close to ceiling is 7.1°C and 3.6°C higher than the floor. The courtyard space with its glass roof forms a 'warm air pool' during the daytime, which can heat up upstairs bedrooms. Without the glass roof, the 'warm air pool' cannot be formed. Figure 7 shows mean air temperatures of upstairs and downstairs bedrooms. Mean temperatures of the two upstairs bedrooms are higher than the downstairs west bedroom. The downstairs east bedroom has the highest mean temperature because there is less shading from the north part of house. Mean air temperatures of downstairs east bedroom and west bedroom, and upstairs middle bedroom and east bedroom are 17.5 ºC, 15.5 ºC, 17.3 ºC and 17.3 ºC respectively, which meet the requirement of minimum indoor temperature 16 ºC of the New Zealand code. The bedrooms of the 'wind-rain' house have good thermal conditions under Auckland winter climate conditions.

Table.1 Indoor thermal conditions of the 'wind-rain' house during the winter

Indoor Spaces	Air Temperature Ranges								Mean T
	>12°C	>14°C	>16°C	>18°C	>20°C	>22°C	>24°C	>26°C	
	Percentage of Winter Time								
North living room (ceiling)	93.4%	94.4%	70.7%	46.0%	29.2%	12.3%	6.2%	2.1%0	17.8°C
North living room (floor)	86.9%	75.6%	39.9%	9.9%	1.2%0	0%	0%	0%	15.2°C
Greenhouse space (ceiling)	86.0%	67.5%	61.2%	48.9%	37.4%	29.6%	26.3%	21.0%	17.8°C
Greenhouse space (middle)	91.8%	73.7%	68.2%	48.1%	21.8%	16.0%	3.7%	1.2%	17.3°C
Greenhouse space (floor)	86.4%	65.7%	28.8%	7.81%	0.4%	0%	0%	0%	14.7°C
South upstairs bedroom (ceiling)	96.3%	87.3%	65.9%	37.8%	20.1%	6.6%	1.6%	0.2%	17.1°C
South upstairs bedroom (floor)	93.0%	81.8%	51.4%	18.9%	3.29%	0%	0%	0%	15.8°C
South upstairs East bedroom (ceiling)	90.6%	88.1%	58.8%	39.4%	23.4%	1%	0.4%	0%	16.3°C
South upstairs East bedroom (floor)	84.4%	72.7%	41.9%	12.3%	1.2%0	0%	0%	0%	15°C
South downstairs East bedroom (ceiling)	99.6%	97.5%	86.7%	60.4%	18.5%	2.9%	0.4%	0%	18.2°C
South downstairs East bedroom (floor)	95.1%	45.6%	43.3%	11.1%	3.3%0	0%	0%	0%	15.4°C
South downstairs West bedroom (ceiling)	92.0%	75.8%	52.2%	26.7%	7.8%	1.2%	0%	0%	15.9°C
South downstairs West bedroom (floor)	87.3%	57.9	23.6%	2.5%	0%	0%	0%	0%	14.4°C
Outdoor North	46.7%	17.7%	3.9%	0.6%	0%	0%	0%	0%	11.1°C
Outdoor South	55.5%	29.6%	7%	0.8%	0%	0%	0%	0%	11.5°C

Table.2 Indoor thermal conditions of an Auckland conventional house during the winter (Su 2006)

Indoor Spaces	Air Temperature Ranges						Mean T
	>15ºC	>16ºC	>17ºC	>18ºC	>19ºC	>20ºC	
	Percentage of Winter Time						
North upstairs double bedroom ceiling	52%	37%	24%	10%	5%	2%	15.4ºC
North upstairs double bedroom floor	52%	30%	10%	3%	0.5%	0%	15.1ºC
North downstairs living room ceiling	65%	41%	16%	7%	2%	0.5%	15.7ºC
North downstairs living room floor	40%	12%	3%	0.5%	0%	0%	14.7ºC
South upstairs bedroom ceiling	38%	16%	5%	0.5%	0%	0%	14.4ºC
South upstairs bedroom floor	27%	16%	2%	0%	0%	0%	14.1ºC
South downstairs bedroom ceiling	51%	22%	6%	0%	0%	0%	14.7ºC
South downstairs bedroom floor	15%	0.5%	0%	0%	0%	0%	14.1ºC
Outdoor	8%	3%	0.5%	0%	0%	0%	11.1ºC

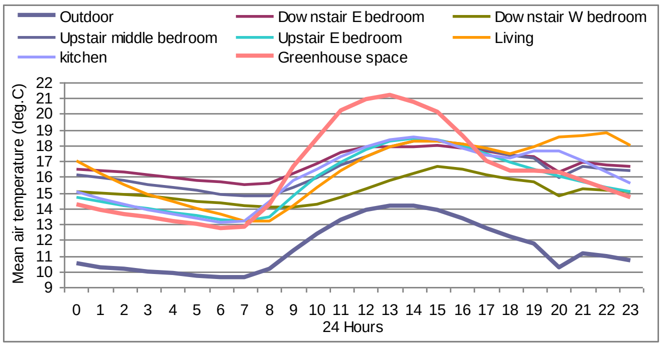

Fig.4 Hourly mean temperatures during the winter months of the 'wind-rain' house

Table.3 Mean temperatures of indoor spaces during the winter daytime from 9am to 6pm

Indoor Spaces	Downstairs E Bedroom	Downstairs W Bedroom	Upstairs bedroom	Upstairs E Bedroom	Living	Kitchen	Greenhouse space
Mean temperature	17.5 ºC	15.5 ºC	17.3 ºC	17.3 ºC	17.1 ºC	17.5 ºC	19.3 ºC
Percentage of time when mean tem. ≥16 ºC	100%	60%	90%	90%	80%	100%	100%
Percentage of time when mean tem. ≥18 ºC	70%	0%	50%	50%	60%	50%	70%
Percentage of time when mean tem. ≥20 ºC	0%	0%	0%	0%	0%	0%	50%

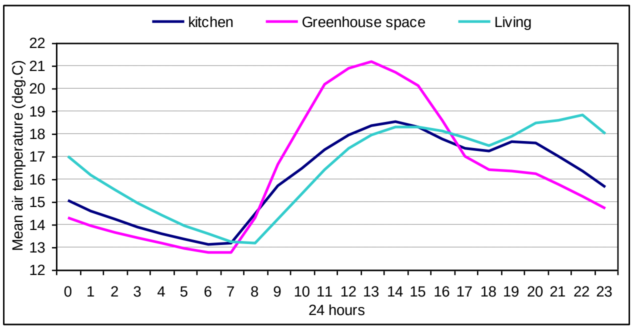

Fig.5 Mean air temperatures of the courtyard space and downstairs kitchen and living

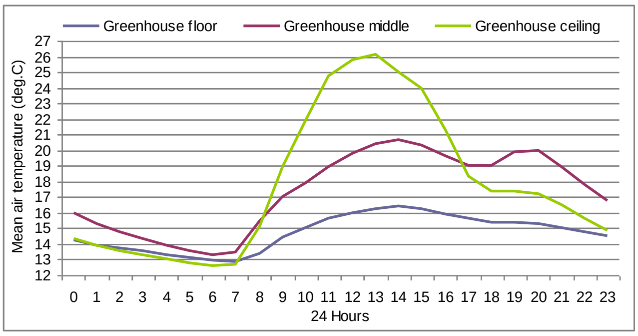

Fig.6 Mean air temperatures of the courtyard space of the 'wind-rain' house

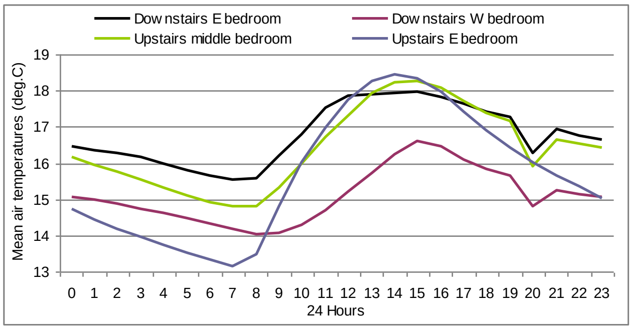

Fig.7 Mean air temperatures of upstairs and downstairs bedrooms

3. ENERGY EFFICIENCY:

The mean winter extra energy consumption of the 200 Auckland sample houses (Su, 2009), which had been using electricity as their only energy source, is used to evaluate the 'wind-rain' house energy efficiency. The 200 sample houses with sufficient insulation within their envelopes according the New Zealand Standard include 90 one-storey houses, 104 two-storey houses and 6 three-storey houses. The range of floor areas is 31 – 446m^2 with a mean floor area of 182m^2. The range of occupancy per dwelling is 1 – 7 persons with a mean number of occupants per dwelling of 3.4 persons. The range of floor areas per occupant is 20 – 180m^2 with a mean floor area per occupant of 65m^2. There are 69 houses with metal roofs (15 houses with brick walls and 54 houses with weatherboard and other walls), 116 houses with concrete tile roofs (78 houses with brick veneer walls and 38 houses with weatherboard and other walls) and 15 houses with cedar shingle roofs or other roofing materials. There are 158 houses with internal garages and 42 houses without. The 'wind-rain' house, which had been using electricity as their only energy source, for this study is two-storey house without internal garage and with sufficient insulation for Auckland. The floor area is 170m^2. About 23.5m^2 floor area is under the glass roof and 146.5 m^2 is under the normal metal roof. Occupants of the 'wind-rain' house are 6. The mean floor area per occupant of the 'wind-rain' house is 28m^2.

Table 4 shows energy consumptions of the 'wind-rain' house and the average of energy consumptions of the 200 Auckland conventional houses. Annual energy consumption, winter energy consumption and energy consumption of other months of the 'wind-rain' house are 89.5% of the average of annual energy consumption, 80.4% of the average of winter energy consumption and 93% of the average of energy consumption of other months of the 200 conventional houses. Energy consumptions of the 'wind-rain' house are lower than the average of energy consumptions of Auckland conventional houses. The difference between mean daily electricity usage in the winter months (June, July and August) and the other months of the 'wind-rain' house, which represents the winter extra energy consumption, is significantly lower than and only 48.1% of the average of the 200 conventional houses. The 'wind-rain' house uses much less winter extra energy, which mainly comprises space heating, extra energy for hot water and all appliances, which are impacted by the winter indoor thermal conditions of a house. The less winter extra energy consumption represents the response of better indoor space thermal conditions of the 'wind-rain' house to the Auckland winter climate conditions. The 'wind-rain' house's energy efficiency is better than the average of the conventional local houses under the local climate.

Table.4 Energy consumptions of the 'wind-rain' house and the 200 conventional houses

Energy consumption (kWh/m3day)	**200 Auckland conventional houses**	**The 'wind-rain' house including greenhouse space**	**The 'wind-rain' house excluding greenhouse space**
Annual energy	0.0592	0.0530	89.5% of 200 houses
Winter energy	0.0754	0.0606	80.4% of 200 houses
Energy of other months	0.0541	0.0503	93.0% of 200 houses
Difference of winter and other months	0.0214	0.0103	48.1% of 200 houses
Ratio of difference to winter energy	28.4%	17.0%	11.4% less than 200 houses

4. INDOOR HEALTH CONDITIONS:

Table 5-6 show percentages of winter time related to different relative humidity ranges of the 'wind-rain' house and the conventional house. Generally, indoor relative humidity level of the 'wind-rain' house is higher than the conventional house during the winter time. Indoor air temperatures of the 'wind-rain' house are higher than the conventional house (see Table 1-2). Indoor diurnal temperature of the 'wind-rain' house is higher than the conventional house and outdoor air temperature because the warm courtyard space can raise indoor air temperatures in a higher level. The warmer air can evaporate and contain more water and the absolute humidity of indoor air can be at a high level unless there is sufficient ventilation for removing the extra moisture during the daytime. When indoor temperatures sharply decrease and windows and vents are closed the indoor relative humidity can sharply increase during the night which can result in the higher relative humidity level of the 'wind-rain' house. The daytime is the best time for window ventilation to remove indoor extra moisture from occupants' daily activities and also decrease indoor relative humidity level when the relative humidity of outdoor space is low. But during the day time, windows of most Auckland houses are closed for the security and the rain protection during the winter day time when the occupants go to work or school. To reduce the indoor relative humidity level, a window designed for the Auckland house should have an adjustable and appropriate area of the window that can be partially opened to obtain an appropriate air change rate by cross ventilation during winter day time but the partially opened window does cause security and rain protection problems when occupants are out of the home (Su, 2006).

For controlling the mould growth on indoor surfaces there could be two options depending on different climate conditions and building designs. One is to use active controls such as permanent heating and mechanical ventilation to keep the indoor relative humidity level under

60%, the threshold of mould survival and growth for a building that is designed for permanent active controls. For indoor air quality, current international and national standards (ASHRAE Standard 62-2000, New Zealand Standard 4303-1990, ANSI/ASHRAE 55-1992, ASHRAE Handbook of Fundamentals 1993) the indoor relative humidity should be lower than 60% to minimize the mould growth. 60% relative humidity is the threshold for mould survival and growth after the germination of mould spores. It is difficult for Auckland houses to maintain indoor relative humidity level under 60% by passive controls. To attain this Auckland houses must rely on active controls such as permanent heating and mechanical ventilation. However from the thermal design point of view, most Auckland houses are designed for temporary heating not for permanent heating as air temperatures during the Auckland winter are normally higher than 5 °C. A second option is to use passive design and passive controls. These can maintain the indoor relative humidity level under 80% which is the threshold of mould germination for a building that is not designed for permanent active controls. If the mould spores never start germination the moulds never grow on indoor surfaces (Su, 2006).

Table 7 shows the threshold of relative humidity and the time required for mould germination. Table 8 shows the number of winter days and the relative humidity ranges of the conventional house which does not have mould problems and where indoor relative humidity levels are lower than the threshold of mould germination. In the wind-rain house of this study there are two indoor spaces - the upstairs east bedroom and the downstairs west bedroom - in which indoor relative humidity levels were higher than 80% - the threshold of mould germination - for over 30 days during the winter (see Table 9). These indoor spaces of the 'wind-rain' house have potential mould growth problems, which do not directly connect with the courtyard space. Lack of ventilation can cause high relative humidity of the two indoor spaces. Sufficient insulation within the house envelop is the first key factor to control the indoor relative humidity level under the threshold of mould gemmation. Winter day time cross ventilation and exhaust fan ventilation in the high moisture concentrated indoor space are also important factor to remove the extra moisture from occupant activities and reduce indoor relative humidity level when the outdoor relative humidity is lower than the indoor relative humidity (Su, 2006).

Table.5 Percentage of winter time and relative humidity ranges of the 'wind-rain' house

Indoor Spaces	Relative Humidity Ranges						Mean RH
	>50%	>60%	>70%	>80%	>90%	=100%	
	Percentage of Winter Time						
Living room (ceiling)	93.8%	65.1%	31.6%	1.6%	0%	0%	65%
Living room (floor)	100%	98.7%	75.3%	16.4%	0.8%	0%	73.7%
Greenhouse space (ceiling)	82.7%	79.3%	59.6%	10.7%	0%	0%	67.5%
Greenhouse space (middle)	97.1%	78.2%	45.6%	6.2%	0.4%	0%	67.5%
Greenhouse space (floor)	99.6%	98.8%	80.1%	23.8%	0.2%	0%	75.5%
Upstairs middle bedroom (ceiling)	99.2%	89.3%	60.4%	9.0%	2.7%	0%	70.4%
Upstairs middle bedroom (floor)	100%	98.0%	83.4%	15%	0%	0%	74.5%
Upstairs east bedroom (ceiling)	98.8%	87.3%	51.8%	3.7%	0%	0%	69.7%
Upstairs east bedroom (floor)	99.6%	99.2%	71.9%	25.5%	0.4%	0%	74%
Downstairs east bedroom (ceiling)	94.7%	53.0%	8.2%	0%	0%	0%	60%
Downstairs east bedroom (floor)	100%	94.5%	60.8%	7.0%	0%	0%	71.1%
Downstairs west bedroom (ceiling)	99.2%	94.5%	78.9%	37.0%	0.8%	0%	75.9%
Downstairs west bedroom (floor)	100%	99.6%	89.1%	17.7%	0%	0%	76.2%
Outdoor	100%	98%	75%	77%	64%	38%	89%

Table.6 Percentage of winter time and relative humidity ranges of a conventional house

Indoor Spaces	Relative Humidity Ranges						Mean RH
	>50%	>60%	>70%	>80%	>90%	=100%	
	Percentage of Winter Time						
North upstairs bedroom ceiling	95%	78%	40%	0.5%	0%	0%	66%
North upstairs bedroom floor	99.5%	87%	66%	0.5%	0%	0%	67%
North downstairs living room ceiling	97%	73%	7%	0.5%	0%	0%	63%
North downstairs living room floor	99.5%	95%	56%	4%	0%	0%	71%
South upstairs bedroom ceiling	99.5%	92%	39%	0%	0%	0%	68%
South upstairs bedroom floor	100%	99.5%	71%	0%	0%	0%	72%
South downstairs bedroom ceiling	100%	99.5%	72%	0%	0%	0%	72%
South downstairs bedroom floor	100%	99%	82%	9%	0%	0%	75%
Outdoor	100%	95%	82%	69%	54%	42%	88%

Table.7 Threshold of relative humidity and time required for mould gemmation

Substrate	Threshold RH	Time Required
Porous and dust and fat covered non-porous	100 %	1 day
	89%	7 day
	80%	30 days

Figure.8 Number of winter days and relative humidity ranges of a conventional house

Indoor Spaces	Relative Humidity Ranges					
	>50%	>60%	>70%	>80%	>90%	=100%
	Days of Winter Time (day)					
North upstairs bedroom ceiling	114	93.6	48	0.6	0	0
North upstairs bedroom floor	119.4	104.4	79.2	0.6	0	0
North downstairs living room ceiling	116.4	87.6	8.4	0.6	0	0
North downstairs living room floor	119.4	114	67.2	4.8	0	0
South upstairs bedroom ceiling	119.4	110.4	46.8	0	0	0
South upstairs bedroom floor	120	119.4	85.2	0	0	0
South downstairs bedroom ceiling	120	119.4	86.4	0	0	0
South downstairs bedroom floor	120	118.8	98.4	10.8	0	0
Outdoor	120	114	98.4	82.8	64.8	50.4

Table.9 Number of winter days and relative humidity ranges of the 'wind-rain' house

Relative Humidity Ranges	Relative Humidity Ranges					
	>50%	>60%	>70%	>80%	>90%	=100%
	Days of Winter Time (day)					
Living room (ceiling)	113	78	38	2	0	0
Living room (floor)	120	118	90	20	1	0
Greenhouse space (ceiling)	99	95	72	13	0	0
Greenhouse space (middle)	117	94	55	7	0	0
Greenhouse space (floor)	120	119	96	29	0	0
Upstairs middle bedroom (ceiling)	119	107	72	11	3	0
Upstairs middle bedroom (floor)	120	118	100	18	0	0
Upstairs east bedroom (ceiling)	119	105	62	4	0	0
Upstairs east bedroom (floor)	120	119	86	31	0	0
Downstairs east bedroom (ceiling)	114	64	10	0	0	0
Downstairs east bedroom (floor)	120	113	73	8	0	0
Downstairs west bedroom (ceiling)	119	113	95	44	1	0
Downstairs west bedroom (floor)	120	120	107	21	0	0
Outdoor	120	116	89	77	53	0

5. Conclusion

The study finds that the 'wind-rain' house has strong advantages on indoor thermal comfort during the winter time. According to field study data, the 'wind-rain' house has better winter indoor thermal condition than the conventional house. The mean temperature of the courtyard space is 19.2°C from 9am to 6pm, which is a very comfortable indoor space for the winter daytime living. The mean temperatures from 9am to 6pm of all other indoor spaces are from 15.5 to 17.5°C, which meet the requirement of the minimum indoor temperature 16°C only for aged care facilities and early childhood centers of New Zealand Standard.

The architectural features of the 'wind-rain' house are different from those of a conventional house. The building layout is altered from the usual orientation plan for a conventional house to a courtyard plan in the case of the 'wind-rain' house. Since a conventional house has an insulated roof and walls, most of the exterior blocks out solar energy. Direct sunlight can only get into the house through windows and glazed doors. Correct orientation is very important to ensure the living space windows catch the strong northern sun. The 'wind-rain' house with its glazed roof courtyard can receive more direct sunlight than a conventional house. The glazed roof not only traps solar energy within the space beneath but can also protect the courtyard space against winter wind and rain. As the sunlight directly enters the courtyard through the glazed roof, the 'wind-rain' house always has the equivalent of two north walls: one in the courtyard and a conventional one outside, which can receive direct sunlight.

The concept or calculation of the ratio the building's external surface to the building volume of the 'wind-rain' house (including or excluding the courtyard) is different from a conventional house. As the 'wind-rain' house forms two different living zones for the daytime and night time, the external surfaces which are subject to heat loss during day and night are different. During the winter daytime, the walls between the courtyard and other indoor spaces which can be opened in order to benefit from solar heat should be counted as internal walls, while the external surface of the 'wind-rain' house should include the glazed roof as well as the walls of the courtyard. During the winter night, the air temperature of the courtyard is lower than that of the other indoor spaces adjacent to the courtyard. Therefore the doors and windows in the walls between the courtyard and other indoor spaces are closed to reduce the heat loss into the courtyard. Thus the walls between the courtyard and other indoor spaces should be counted as external walls when designing and building for thermal comfort.

The concept of the indoor space arrangement of the 'wind-rain' house is different from that of a conventional house. The concept of the indoor space arrangement of a conventional house is based on the customary north orientation of the building and attempts to position the main living room or bedroom on the warm side of house, which can obtain direct sunlight and benefit from passive solar heating energy, and place service spaces such as the toilet or bathroom on the cold side of house. For the 'wind-rain' house, the north section and the south section of the courtyard are both warm sides, so the concept of the indoor space arrangement of the 'wind-rain' house is based on appropriate relationships with the courtyard. Therefore the indoor space arrangement of the 'wind-rain' house can be more flexible and is not limited by the orientation of building, as regards winter thermal comfort.

The 'wind-rain' house's energy efficiency is better than the average of the conventional local houses in the local climate. Energy consumption of the 'wind-rain' house is lower than the average of energy consumption of the Auckland conventional house. The difference between mean daily electricity usage in the winter months (June, July and August) and the other months of the 'wind-rain' house, which represents the winter extra energy consumption, is significantly lower than, and only 48.1% of, the average of the 200 conventional houses. The 'wind-rain' house uses much less winter extra energy, which mainly comprises space heating, extra energy for hot water and all appliances, which are impacted by the winter indoor thermal conditions of a house. The less winter extra energy consumption represents the response of better indoor space thermal conditions of the 'wind-rain' house to the Auckland winter climate conditions. The 'wind-rain' house's energy efficiency is better than average of the conventional local houses in the local climate.

Improvement of the 'wind-rain' house design should focus on decreasing indoor relative humidity, which is related to health effects. Generally, indoor relative humidity level of the 'wind-rain' house is higher than the conventional house during the winter time according the data of field studies. This study identify that there are two indoor spaces: upstairs east bedroom and downstairs west bedroom, in which indoor relative humidity level are higher than 80% the threshold of mould germination for over 30 days during the winter time. Those indoor spaces of the 'wind-rain' house potentially have mould growth problems. The further study with more samples of 'wind-rain' houses is needed to develop the detail design guides for thermal comfort and energy efficiency and the improvement of indoor health conditions in the local climate.

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