

Impacts of the Courtyard with Glazed Roof on House Winter Thermal Conditions

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Abstract—The ‘wind-rain’ house has a courtyard with glazed roof, which allows more direct sunlight to come into indoor spaces during the winter. The glazed roof can be partially opened or closed and automatically controlled to provide natural ventilation in order to adjust for indoor thermal conditions and the roof area can be shaded by reflective insulation materials during the summer. Two field studies for evaluating indoor thermal conditions of the two ‘wind-rain’ houses have been carried out by author in 2009 and 2010. Indoor and outdoor air temperature and relative humidity adjacent to floor and ceiling of the two sample houses were continuously tested at 15-minute intervals, 24 hours a day during the winter months. Based on field study data, this study investigates relationships between building design and indoor thermal condition of the ‘wind-rain’ house to improve the future house design for building thermal comfort and energy efficiency

Keywords—Courtyard, house design, indoor thermal comfort, ‘wind-rain’ house

I. INTRODUCTION

ONE Auckland ‘wind-rain’ house and one Wellington ‘wind-rain’ house are used for the field studies in 2009 and 2010. The Auckland house contains three sections (see Fig. 1-2). The north living section (one storey) contains the enclosed living room on the west side and, open to the courtyard, the kitchen and dining room to the east. The middle section is the courtyard space itself with a glass roof and east and west glazed walls. The south sleeping section of two storeys has three bedrooms upstairs, and, downstairs two bedrooms with a large utility area in between, which opens off the courtyard. In respect to the study’s results it is noted that the three bedrooms at either end are the only rooms not adjacent to the courtyard. The total floor area is 170m². About 23.5m² of the floor area is under the glass roof and 146.5m² is under the normal metal roof. The Wellington one-storey ‘wind-rain’ house (see Fig. 3-4) has a courtyard located in the centre of house surrounded by different indoor spaces. The master bedroom with bathroom is in the south-east corner of house. The open living space including living, dining and kitchen is in south side of house for catching the good sea view. There is no partition between the open living space and the courtyard. Another bedroom with dressing room is in the north-west corner of house. Another bathroom and laundry are in the north-east corner of house and the entry with glazed roof is in north side of house. The total floor area is 104.8m². About 23.5m² of the floor area including courtyard (17.3m²) and entry (6.2 m²) is under the glass roof and 81.3m² is under the normal metal roof.



Fig. 1 The Auckland ‘wind-rain’ house for the field study in 2009

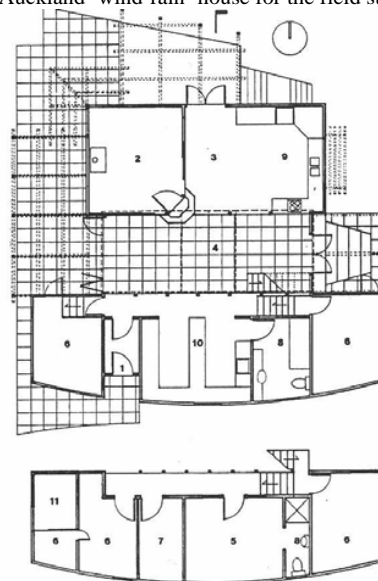


Fig. 2 The Auckland ‘wind-rain’ house plans



Fig. 3 The Wellington ‘wind-rain’ house for the field study in 2010

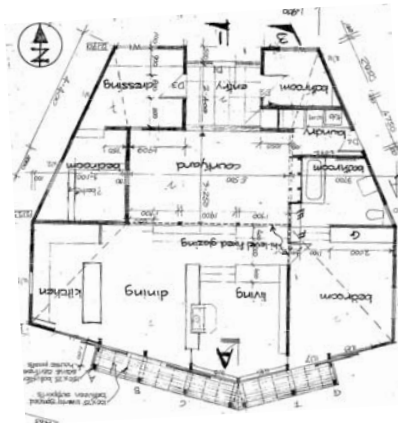


Fig. 4 The Wellington 'wind-rain' house plans

Fig. 5 shows Auckland and Wellington monthly mean maximum and minimum temperatures. Auckland and Wellington have a temperate climate with comfortable summer and mild winter. The winter temperatures are lower than the comfort zone (18°C to 28°C) but rarely below the 5°C. Thermal design of Auckland and Wellington houses should mainly focus on the thermal performance during winter [1], [2]. Field studies of an Auckland 'wind-rain' house during the winter of 2009 [3] and a Wellington 'wind-rain' house during the winter of 2010 focus on investigating winter thermal and health conditions. Indoor and outdoor air temperature and relative humidity adjacent to floor and ceiling of different indoor spaces were continuously measured at 15-minute intervals 24 hours a day during the winter months by Escort Data Loggers. Field study data were converted into percentages of time related to different temperature ranges, hourly mean temperatures of winter months and daily mean temperature profiles of the winter months in different indoor spaces of two 'wind-rain' houses, which are used to evaluate indoor thermal comfort and energy efficiency in comparison with the conventional houses.

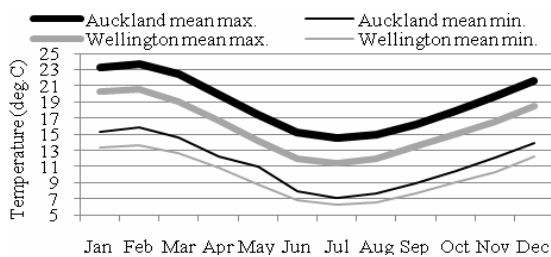


Fig. 5 Auckland and Wellington monthly mean maximum and minimum temperatures (source: NIWA)

II. INDOOR THERMAL CONDITIONS OF TWO 'WIND-RAIN' HOUSES

The World Health Organization recommends a minimum indoor temperature for houses of 18°C; and 20-21°C for more vulnerable occupants, such as older people and young children. The current New Zealand Building Code does not have a general requirement for the minimum indoor air temperature of a house, although it has a requirement of 16°C

for more vulnerable occupants, such as older people and young children [4]-[7]. The Auckland 'wind-rain' house has a much higher percentage of comfortable winter time (for example, 16°C, 18°C or 20°C) and higher mean temperatures than the Auckland conventional house under the similar outdoor mean temperature (see Table 1-2). The Wellington 'wind-rain' house also has a much higher percentage of comfortable winter time (for example, 16°C, 18°C or 20°C) and higher mean temperatures when the outdoor mean temperature is lower than the Auckland conventional house (see Table 2-3). The 'wind-rain' house provides superior winter indoor thermal comfort conditions to those of the conventional house.

TABLE I
WINTER TIME WITH DIFFERENT TEMPERATURE RANGES OF AUCKLAND 'WIND-RAIN' HOUSE

Indoor Spaces	Air Temperature Ranges			Mean(°C)
	>16° C	>18° C	>20° C	
	Percentage of Winter Time			
Living(ceiling)	71%	46%	29%	17.8
Living(floor)	40%	10%	1%	15.2
Courtyard(ceiling)	61%	49%	37%	17.8
Courtyard(middle)	68%	48%	22%	17.3
Courtyard(floor)	29%	8%	0%	14.7
Ups. Bed.(ceiling)	66%	38%	20%	17.1
Ups. Bed.(floor)	51%	19%	3%	15.8
Ups. E Bed.(ceiling)	59%	39%	23%	16.3
Ups. E Bed.(floor)	42%	12%	1%0	15.0
Down. E Bed.(ceiling)	87%	60%	19%	18.2
Down. E Bed.(floor)	43%	11%	3%0	15.4
Down. W				15.9
Bed.(ceiling)	52%	27%	8%	
Down. W Bed.(floor)	24%	3%	0%	14.4
Outdoor North	4%	0.6%	0%	11.1
Outdoor South	7%	0.8%	0%	11.5

TABLE II
WINTER TIME WITH DIFFERENT TEMPERATURE RANGES OF AUCKLAND CONVENTIONAL HOUSE [1]

Indoor Spaces	Air Temperature Ranges			Mean(°C)
	>16°C	>18°C	>20°C	
	Percentage of Winter Time			
N Ups. Bed.(ceiling)	37%	10%	2%	15.4
N Ups. Bed.(floor)	30%	3%	0%	15.1
N Down. living(ceiling)	41%	7%	1%	15.7
N Down. living(floor)	12%	1%	0%	14.7
S Ups. Bed.(ceiling)	16%	1%	0%	14.4
S Ups. Bed.(floor)	16%	0%	0%	14.1
S Down. Bed.(ceiling)	22%	0%	0%	14.7
S Down. Bed.(floor)	1%	0%	0%	14.1
Outdoor	3%	0%	0%	11.1

TABLE III
WINTER TIME WITH DIFFERENT TEMPERATURE RANGES OF WELLINGTON 'WIND-RAIN' HOUSE

Indoor Spaces	Air Temperature Ranges			Mean (°C)
	>16° C	>18° C	>20° C	
	Percentage of Winter Time			
Bathroom (floor)	22%	1%	0%	15.0
Courtyard (floor)	25%	1%	0%	14.9
Courtyard (ceiling)	47%	29%	20%	17.1
Dinning (Floor)	20%	5%	1%	14.2
Dinning (ceiling)	44%	20%	8%	15.8
N Bed. (floor)	29%	7%	1%	15.1
N Bed. (ceiling)	62%	31%	11%	16.7
S Bed. (floor)	13%	0%	0%	14.3
S Bed. (ceiling)	64%	18%	2%	16.5
Outdoor	5%	2%	1%	10.5

Fig. 6-7 show hourly mean temperature profile of 24 hours during the winter months from June to August of different indoor spaces of two sample houses. The lowest indoor temperatures occur at about 7-8am; the indoor spaces are initially warmed up by the sun at about 9am; then the indoor mean temperatures reach their highest level at about 2-3pm; and after that peak temperature, the indoor mean temperatures steadily decrease. After 5pm the decreasing trends of the indoor mean temperatures are affected by the heat from the cooking of the open kitchen or temporary heating during the early evening. Then from the middle of the night indoor temperatures steadily decrease to their lowest indoor levels. During the winter daytime from 9am to 5pm, the hourly mean temperatures of the courtyard are significant higher than the other indoor spaces and the minimum hourly mean temperature is higher than 16 °C. The courtyard is a very comfortable place for its occupants during the winter daytime.

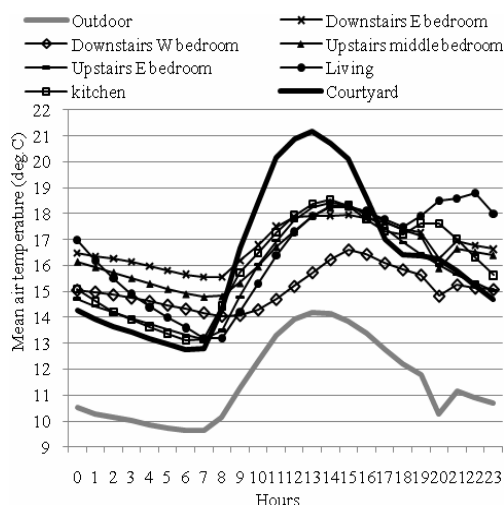


Fig. 6 Indoor hourly mean temperatures of the Auckland 'wind-rain' house

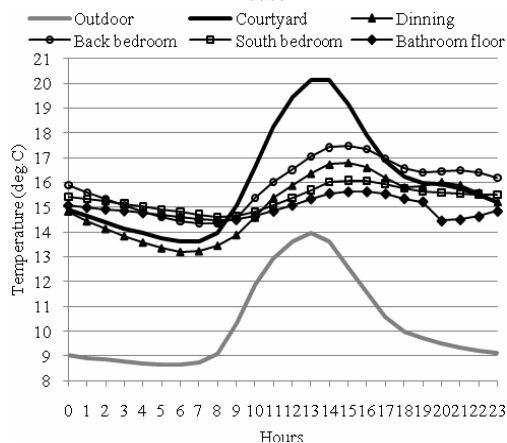


Fig. 7 Indoor hourly mean temperatures of the Wellington 'wind-rain' house

III. WINTER THERMAL IMPACTS OF COURTYARD WITH GLAZED ROOF ON HOUSE DESIGN

For the design of a house with a glazed courtyard, some conventional design concepts or rules, certain architectural features and thermal performance of building elements are different from those of a conventional house, which can be utilized to improve house design for thermal comfort and energy efficiency.

A. Design rule for direct sunlight

The 'wind-rain' house can access more direct sunlight and solar energy not only through its windows but also through its courtyard roof. The conventional house with the insulated roof and walls keeps out most of direct sun light and solar energy. The direct sun light can only get into indoor spaces through the windows faced to the north. Conventional rule of locate house design is based on the right orientation and sufficient window area faced to the equator for direct sunlight. The 'wind-rain' house can access more direct sunlight and solar energy not only through its windows but also through its courtyard roof. The winter daily solar radiation on the vertical surface is higher than the horizontal surface, for example, the Auckland winter daily solar radiation on a horizontal surface (2.3kWh/day/m^2) is 60% higher than on a vertical surface (1.4kWh/day/m^2) [8]. The 'wind-rain' house has an indoor courtyard with a glazed roof, which is bigger than the window area of a conventional house. The glazed roof not only allows more direct sunlight to come into the courtyard, which warms up the courtyard space and the indoor spaces adjacent to the courtyard, but also the glazed roof can trap warm air within the courtyard without being affected by wind. The 'wind-rain' house can utilize more passive solar heating energy than a conventional house, which make indoor temperatures higher than the conventional house (see Table 1-3).

B. Concept of living zone

The 'wind-rain' house provides different living zones for different time of a day. Table 4-5 show indoor mean temperatures of the Auckland and the Wellington 'wind-rain' houses during the winter daytime from 9am to 5pm. Daytime mean temperatures in the courtyards are $18.2\text{ }^\circ\text{C}$ and $19.3\text{ }^\circ\text{C}$, which are at least $2\text{-}3\text{ }^\circ\text{C}$ higher than other indoor spaces. The courtyard is a very comfortable place and a better living place than other indoor spaces during the winter daytime. The mean temperatures of other indoor spaces range from 15.5 to $17.5\text{ }^\circ\text{C}$, which meet the requirement for a minimum indoor temperature of $16\text{ }^\circ\text{C}$ for more vulnerable occupants, such as older people and young children, as set out in the New Zealand Standard. After midnight, mean temperatures of most indoor spaces are higher than the courtyards. Other indoor spaces are not only comfortable places during the winter daytime but also better living places than the courtyards during the winter night.

TABLE IV
WINTER DAYTIME MEAN TEMPERATURES OF AUCKLAND 'WIND-RAIN' HOUSE

Indoor Spaces	Air Temperature Ranges			Mean(°C)
	>16°C	>18°C	>20°C	
Percentage of Winter Day Time				
Courtyard	100%	70%	50%	19.3
Living	80%	60%	0%	17.1
Ups. Bed.	90%	50%	0%	17.3
Ups. E Bed.	90%	50%	0%	16.3
Down. E Bed.	100%	70%	0%	17.5
Down. W Bed.	60%	0%	0%	15.5

TABLE V
WINTER DAYTIME MEAN TEMPERATURES OF WELLINGTON 'WIND-RAIN' HOUSE

Indoor Spaces	Air Temperature Ranges			Mean (°C)
	>16°C	>18°C	>20°C	
Percentage of Winter Day Time				
Courtyard	89%	67%	33%	18.2
Dinning	67%	0%	0%	15.8
N Bed.	78%	11%	0%	16.5
S Bed.	56%	0%	0%	15.5

C. Concept of indoor and outdoor space

For building thermal design, concept of indoor and outdoor spaces of the 'wind-rain' house is different from the conventional house. The external wall of a conventional house normally is the boundary between indoor and outdoor space. The 'wind-rain' house has a courtyard with a glazed roof and provides two living zones for different times of a day. Fig. 8 shows the mean air temperatures of the courtyard space and downstairs kitchen and living room of the Auckland 'wind-rain' house. 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 also a more negative impact during the night time on the indoor thermal conditions of the kitchen, than it does on the living room with its partition wall. During the winter daytime, the courtyard is one of the comfortable indoor living spaces. During the winter night, the courtyard mean temperature is lower than other indoor spaces. For building thermal design and energy efficiency, the courtyard should be considered as an outdoor or semi-outdoor space for the indoor spaces, which are adjacent to the courtyard, during the winter night.

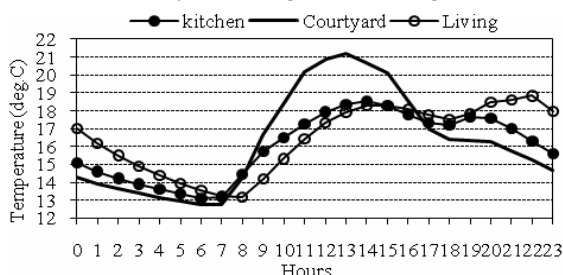


Fig. 8 Winter indoor hourly mean temperatures of the Auckland 'wind-rain' house

D. Concept of indoor space arrangement

The concept of the indoor space arrangement of the sample house is different from that of a conventional house. The orientation is very important for the north side walls and

windows of the conventional house to catch the direct sunlight. 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 the 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 the house. 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. 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 sample 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 the building, as regards winter thermal comfort.

E. Ratio of building surface to volume

Ratio of building surface to volume is one of the most important design factors for thermal comfort and energy efficiency. The concept or calculation of the ratio of 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 sample house forms two different living zones for the daytime and nighttime, the external surfaces which are subject to heat loss during the 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 sample 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.

F. Courtyard

The thermal performances of the 'wind-rain' house's courtyard for thermal building design are different from a conventional courtyard. A conventional courtyard in a hot-dry climate is an area wholly or partly enclosed by walls or buildings and open to the sky, which also supplies shading, reduces wind speed and dust, maintains moisture and encourages heat loss from the indoor spaces during the night, etc. The glazed roof of the 'wind-rain' house's courtyard can still receive direct sunlight and trap passive solar heat energy, as well as supply protection from wind and rain, and reduce heat loss during the night, etc. Fig. 9-10 show the air temperatures close to the ceiling and the floor of the courtyards of Auckland and Wellington 'wind-rain' houses during the winter. Air temperatures close to the ceiling fluctuate greatly and most of the daytime from 9am to 5pm the air

temperatures close to the ceiling are over 20°C. Fig. 11-12 show hourly mean temperatures close to the ceiling and the floor of courtyards of Auckland and Wellington ‘wind-rain’ house. The maximum hourly mean temperatures close to the ceiling is about 8-9°C higher than the floor of courtyards of Auckland and Wellington ‘wind-rain’ houses during the winter. During the daytime, the courtyard space with its glazed roof creates a ‘warm air pool’ with a large air temperature gradient, which can also heat the upstairs bedrooms. Fig. 13 shows the mean air temperatures of the upstairs and downstairs bedrooms of the Auckland ‘wind-rain’ house. The maximum mean air temperatures of the two upstairs bedrooms are higher than the two downstairs bedrooms during the winter daytime. The ‘warm air pool’ with a large air temperature gradient can positively impact on the thermal comfort of the upstairs indoor spaces. The courtyard with glazed roof can be arranged in different locations within a house. If the courtyard is located in the centre section of a house, there are two north walls and two warm zones: the north and south sections, which is the same design as the Auckland ‘wind-rain’ house, the east or west sections of the house not only can receive direct sunlight in the morning and afternoon, but also can receive direct sunlight from the courtyard and benefit from the warm courtyard. To obtain a desirable view, the main living room has to be located in the south section of the house. The courtyard could be positioned on the south side of the house to create a warm south living section during the daytime. When the site conditions are badly affected by too much shading from surrounding buildings, adverse topographic conditions, or trees on the north side of the building site, the courtyard could be built on the north side to obtain direct sunlight through its roof rather than through the windows of the house. If a courtyard with an irregular shape is sited between different indoor spaces, they can also benefit from the courtyard.

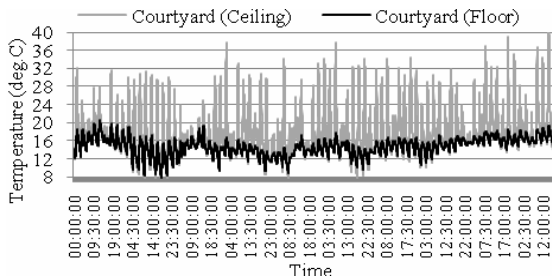


Fig. 9 Indoor temperatures of Auckland ‘wind-rain’ house’ courtyard

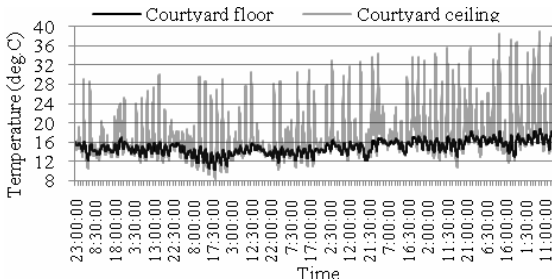


Fig. 10 Indoor temperatures of Wellington ‘wind-rain’ house’s courtyard

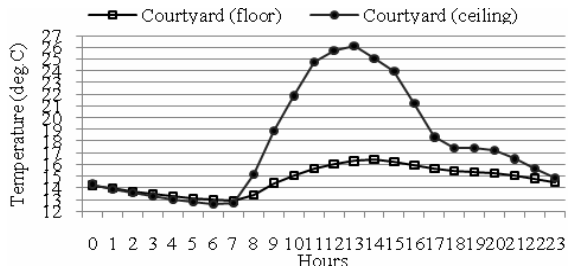


Fig. 11 Mean temperatures of Auckland ‘wind-rain’ house’ courtyard

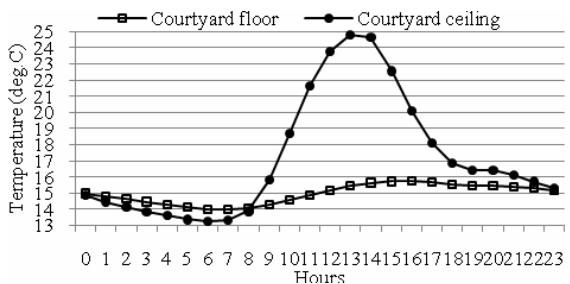


Fig. 12 Mean temperatures of Wellington ‘wind-rain’ house’ courtyard

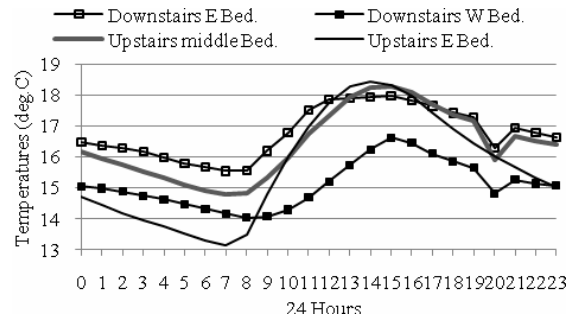


Fig. 13 Mean temperatures of upstairs and downstairs bedrooms

G. Glazed roof of the courtyard

Although the thermal resistance (R-value) of a single layer of glass (0.26 m² °C/W) is very low compared with walls (1-1.9 m² °C/W) and roofs (2.9-3.5 m² °C/W) which are insulated in accordance with the current standard, the glass roof of the sample house can still give the courtyard some protection from heat loss [9]. The underside surface temperature of the glazed roof is much lower than the sky’s temperature and close to the outdoor air temperature, which significantly reduces the heat loss from an occupant’s body through long wave radiation to the glazed roof, as compared with a conventional courtyard open to the sky. After midnight, the mean temperature of the courtyard space is slightly lower than other indoor spaces, but it has much better thermal conditions than the outdoors during the winter night. In fact the mean temperature of the courtyard space is at least 3°C for the Auckland ‘wind-rain’ house and 5°C for the Wellington ‘wind-rain’ house higher (see Fig. 6-7). Without wind flow, the wind chill temperature in a courtyard space with a glazed roof is much higher than for a courtyard open to the sky and outdoor spaces during the winter night. The glazed roof also provides rain protection so the courtyard provides a comparatively comfortable space for its occupants

during on winter nights. Also at night, rain and overcast skies can reduce the heat loss from the glazed roof to the sky with the much lower temperature, so the thermal comfort conditions in a courtyard with a glazed roof are superior. The optimum design feature of the glazed roof is its ability to obtain more solar energy during the winter daytime and also reduce heat loss during winter nights. A double glazed roof, different roof materials, removable insulation or roofing material, etc. could be utilized to improve the thermal performance of the glazed roof.

H.Partition

The 'wind-rain' house forms two living zones for daytime and night time use. The walls between the courtyard and the indoor rooms perform two different functions: the internal wall is for daytime and the external wall for night time use. The design of the walls between the courtyard and indoor spaces, which can be maximally opened during the daytime and closed during the night time, is important in order to achieve the best indoor thermal comfort conditions for the 'wind-rain' house during winter. Normally, there is no insulation within the internal walls of a conventional house, but proper insulation within the walls between the courtyard and indoor spaces can improve the thermal comfort of these spaces adjacent to the courtyard during winter nights.

IV. ENERGY EFFICIENCY OF 'WIND-RAIN' HOUSE

Table VI shows energy consumptions (daily energy use per cubic meter of indoor space, kWh/m³day) of the 'wind-rain' house and the average of energy consumptions of the 200 Auckland conventional houses with sufficient insulation [9]. 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 winter extra energy is a smaller portion (17%) of the winter energy of the Auckland 'wind-rain' house than the 200 conventional houses (28.4%). 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 under the local climate.

TABLE VI
ENERGY CONSUMPTIONS OF THE 'WIND-RAIN' HOUSE AND 200 CONVENTIONAL HOUSES IN AUCKLAND [3]

Energy(kWh/m ³ day)	200 houses	Wind-rain	Difference e
Annual	0.0592	0.0530	89.5%
Winter	0.0754	0.0606	80.4%
Other months	0.0541	0.0503	93.0%
Winter extra	0.0214	0.0103	48.1%
Winter extra/winter	28.4%	17.0%	11.4%

V.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. Energy consumptions of a 'wind-rain' house are lower than the average energy consumption of local conventional houses. Especially, the 'wind-rain' house uses much less winter extra energy than locate conventional houses, which is closely related to winter indoor thermal condition of a house.

For the design of the house with a glazed courtyard, some conventional design concepts or rules, certain architectural features and thermal performance of building elements are different from those of a conventional house. Recognizing those differences is very important for a designer to utilize a courtyard with glazed roof in a house design to achieve winter thermal comfort and energy efficiency. Current passive design guides for thermal comfort and energy efficiency of the conventional house are not fully suitable for the design of a house with a glazed courtyard. The study summarizes and expounds those difference and design advantage of the house with glazed courtyard for improving the future house design for thermal comfort and energy efficiency.

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