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Improving comfort levels in a traditional high altitude Nepali house

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Abstract

Humla Province is a remote mountainous region of northwest Nepal. The climate is harsh and the local people are extremely poor. Most people endure a subsistence culture, living in traditional housing. Energy for cooking and heating comes from fuelwood, supplies of which are diminishing. In order to improve the indoor environment and reduce fuelwood use, smokeless stoves are being introduced to replace the open fire in Humli homes. There is some concern, however, that comfort levels may not be as acceptable with these stoves. The aim of this research was therefore to investigate ways in which the comfort levels in traditional Humli housing might be improved using simple and low cost strategies. Temperature data was recorded in four rooms of a traditional Humli home over a 12-day period and used with fuelwood data to validate a TRNSYS simulation model of the house. This model was then used to evaluate the impact on comfort levels in the house of various energy conservation strategies using PMV and PPD indicators. As a single strategy, it was found that reducing infiltration of outside air was likely to be more effective than increasing the insulation level in the ceilings. The most successful strategy, however, was the creation of sunspaces at the entrances to the living rooms. This strategy increased average internal temperatures by 1.7 and 2.3 °C. In combination with increased insulation levels, the sunspaces reduced comfort dissatisfaction levels by over 50%.

Keywords: Nepal; Traditional housing; Comfort; Simulation; Energy conservation

Introduction

Nepal is a developing country and is ranked 142nd out of 177 countries in terms of the Human Development Index [1]. In terms of income, it is ranked 68th out of 102 developing countries with an annual GDP per capita of US$ 252 [2]. In 2004, the country had a population of 26.6 million, of which 40% were aged 15 or less; and approximately 85% of the population lived in rural areas [2]. Traditional fuel consumption represents 93% of the country's total energy usage and the average annual per capita electricity consumption is only 91 kWh. Fuelwood, the traditional source of domestic energy, is burned on an open fire inside most traditional Nepali houses, and this practice results in a poor indoor environment. Indoor pollution impacts adversely on the health of occupants, particularly women and children, e.g. [3] and [4]. In addition, fuelwood is now in short supply in many areas and this means that increasing time is spent travelling to and carrying heavy loads from remaining fuelwood sources.

On the basis of anecdotal evidence and unpublished survey data [5], it has been found that for approximately 10 months of the year, the open fire simultaneously provides a source of heat and light, both of which are vital for domestic life. Heat is particularly important in the mountainous areas of Nepal, where low ambient temperatures are common. In an attempt to reduce fuelwood consumption and improve the indoor environment, smokeless cooking stoves have been introduced into rural Nepal, as in many other developing countries. This is the case in Humla, a remote mountainous region in the northwest of the country, where approximately 2000 smokeless metal stoves have been installed by a local NGO (RIDS-Nepal) since 2002. Quantitative evidence indicates that when properly used a smokeless stove can reduce the indoor PM_{10} level generated by an open fire by over 90%. Unpublished data measured using a portable air monitor (SKC Inc., Model EPAM-5000) shows that over a typical 24-h period the average indoor PM_{10} in a kitchen with a smokeless stove was 0.056 mg m^{-3}, compared to 1.28 mg m^{-3} in a similar kitchen using an open fire place. However, there is some concern that comfort levels may not be as acceptable as before because of a reduction in radiant heat. Since there is a need to continue to introduce improved cooking stoves because of the health benefits, there is also a need to address comfort levels. If comfort levels are not improved, the continued acceptability of the stoves may be compromised.

One approach to improving the comfort level of occupants is to redesign the stoves that are introduced. Another approach, taken in this research, is to analyse the thermal performance of the traditional house and investigate simple ways of improving the building envelope to improve comfort levels. In this research, a validated dynamic model of a traditional house was developed and current comfort levels were predicted. The model was then used to investigate the effects on those comfort levels from changes to the building envelope. The paper initially describes the location of the research and the climate in the region. Previous similar research is then reviewed and the model used in this research and its validation are described. The impact on comfort levels achieved by implementing various energy conservation measures is then predicted using the validated model.

The Humla valley

According to Ref. [6], Nepal can be divided into seven natural topographical “units”, which can be clearly distinguished from each other. One of these regions is known as the Inner Himalayas. It is the name given to the valleys, which lie to the north of Nepal's principal and well-known chain of mountains, the Himalayas. These inner valleys are described by Ref. [6] as “the real high mountain valleys of Nepal, surrounded on all sides as they are by ice clad giants”. One of these valleys, located on the western end of the country, is the Humla valley, which is over 400 km west of Kathmandu.

Of the 75 districts in Nepal, Humla has been judged to be one of the most deprived. Humla ranks second to last in terms of poverty, socio-economic and infrastructural development, and female empowerment [7]. The population of the Humla District is approximately 47,000, which is very low for its district size, resulting in less than 10 persons per km^2[8]. Since the district does not have any road infrastructure, people and goods are transported on foot or by animal along mountain tracks. The climate in Humla is also challenging. Table 1 shows some climatic data collected at the High Altitude Research Station (HARS) of RIDS-Nepal in Simikot between May 2004 and March 2007, inclusively.

Previous research

Although limited, there is some previous research into the thermal performance and associated comfort levels in traditional Nepali houses. A very useful report was prepared by Ref. [9] as part of a project to "develop and apply effective affordable (low-cost) thermal insulation solutions for traditional stone dwellings … in the Northern Areas of Pakistan". Revised for Nepal, the document contains a list of priorities and suggested improvements to the building envelope. These include: closing the open hole in the roof used to vent smoke, applying internal wall insulation, keeping the roof and walls dry, installing a suspended ceiling, installing double glazing and curtains, filling cavity walls with insulation, and keeping foundations dry and insulating the floor.

The performance of a two-storey traditional dwelling in an unspecified mountainous area of Nepal was predicted by Ref. [10]. The dwelling had a total area of 54.5 m^2, each floor being a single room. A modified Japanese heating and cooling load calculation programme was used to perform the simulations. Modifications to the programme were reported to be the addition of "the calculation of natural ventilation rates for a building with multiple compartments" and "the calculation of heating and cooling loads, considering simultaneous heat and moisture flow in the building and existing materials in components". It was found that reducing infiltration by closing of doors and windows, and the addition of roof insulation improved the thermal conditions by between 4.4 and 12.7 K. After reducing fuelwood consumption by 60%, night-time temperatures were still 1.0–4.0 K higher than the unmodified house. The applicability of research of Ref. [10] to Humla Province is, however, limited by several factors. Although often multi-storey, the Humli houses are typically much smaller, and unfortunately the climatic data values used by Ref. [10] are not stated and the hourly variation in measured indoor temperatures is not shown.

A 4-day thermal comfort study of 36 residents in the town of Lomantang in the Mustang District of Nepal was also conducted by Ref. [11]. This area is mountainous, but located at 3705 m, this town is nearly 700 m higher than Simikot, the location of this research. Although both locations experience severe winters, there are some important differences. While the mean monthly outside ambient temperature for the two locations in May is very similar, Simikot is significantly warmer in January. Relative humidity levels for the two locations are also quite different. In Mustang, mean monthly relative humidity levels are reported to be 97% and 71% in January and May respectively, while in Simikot 2006 data indicate average values of 29% and 62%, respectively. The authors in Ref. [11] found that the residents of three houses investigated were “highly satisfied with the thermal conditions of their houses”. The researchers also established that the mean neutral temperature for the surveyed residents was only 10.7 °C, although there was considerable variation in the neutral temperature established in the three houses measured. The detailed analysis used a nine-point scale, in preference to the seven-point scale used by ASHRAE. Because there was no electricity in the houses investigated and residents went to bed at 8 p.m., the study was only conducted in the daytime. The researchers in Ref. [11] established high levels of personal insulation, measured in clo, by weighing clothing. These values were 2.87 for men and 5.96 for women. Body surface areas of 1.57 and 1.44 m^2 were calculated for men and women, respectively. In comparison with most traditional Humli house standards, however, the houses investigated were quite different. Firstly, they were two-storey courtyard houses, where the first storey is used for animals and storage. Secondly, the Mustang houses are constructed from sun dried 450-mm-thick bricks, as opposed to granite rock in Humla. These factors, together with climatic differences, limit the value of the study by Ref. [11] to the present research.

Typical Humli house

A typical Humli house is usually multi-storey. The ground level rooms are used to stable animals, while the middle and upper storeys often consist of a living room and a store room. Such a house was identified in Simikot, the main town of Humla Province and was used for this study. Two adults and four small children permanently occupy the house. The normal routine of this working family is to awaken between 5 and 6 a.m. and to go to bed sometime after 9 p.m. Main meals are eaten twice a day. Breakfast is cooked between 7 a.m. and eaten at about 9 a.m. Cooking dinner begins at about 6 p.m. or after sunset and takes 2–3 h. This meal is eaten between 8 and 9 p.m. Some snacks might be cooked on the stove during the day between 1 and 2 p.m.

The four principal rooms in the house were identified as follows:

• Living Room 1 is on the middle level. It is the main room of the house, containing a smokeless stove and is where the family of six sleep at night.

• Store Room 1 is also on the middle level and is adjacent to Living Room 1

• Living Room 2 is a spare room on the upper level, used by visiting relatives and guests. Two adults occupied this room at the time of this study.

• Store Room 2 is also on the upper level, adjacent to Living Room 2.

The four rooms are small and their principal internal dimensions, together with those of the animal stables, are given in Table 2 and the floor plans of the three levels is shown in Fig. 1.

In front of the rooms on the top and middle levels, a semi-enclosed area has been built with loose-fitting timber (Fig. 2). This construction offers some protection from cold southerly winds off the mountains, but also shades the main wall from solar radiation. These semi-enclosed areas measure 6.0 and 5.6 m^2 for the middle and top levels, respectively. There are also 0.5 m overhangs projecting from roofs of the semi-enclosed areas. The roofs of Levels 1 and 2 are made of various layers of timber, bracken, plastic sheet, slate, finished on top with earth/mud. They serve as the access walkways for the levels above. In this Humli house, there was (from outside to inside) 40 mm of mud, 30 mm of slate, a plastic sheet, 20 mm of bracken and 25 mm of timber, supported on a network of beams.

Fig. 3 shows the middle and top storeys of the houses adjacent to that used for this study. Inaccessibility prevented the actual house from being photographed effectively. Access to other levels is often by log ladders and several of these can be seen in Fig. 3.

The constructional walls are stone, usually 450 mm thick. At ground level, the constructional wall is exposed (Fig. 4), as are the end walls of any particular row of houses. In this instance, the studied house is an “end” house (Fig. 5).

Indoor thermal environment

Ambient conditions inside the house were measured at hourly intervals over a 12-day period in early April 2007. Although the last snow had fallen in early March, ambient temperatures at night still fell below 10 °C every night (Table 3). Battery-powered data loggers (Onset Corp., Hobo H8 Series) were installed in each of the two living rooms and storerooms, in each case at a height of approximately 1.5 m. These devices were cross-calibrated against each other at the start of the experiments. Figs. 5 and 6 show the hourly dry bulb (db) temperature and relative humidity measured in the two living rooms and outside the house over the period and Table 3 provides a summary of those conditions, in terms of an average, maximum and minimum, together with outside ambient conditions.

High temperatures in Living Room 1 are due to the operation of a smokeless stove in that room. The logger was approximately 1.8 m from the stove. The smaller and larger peaks in Fig. 6 show the impact of stove operation in the mornings and evenings, respectively. The mean minimum temperatures are higher in Living Room 1, not only because of the use of the cooking stove, but also because the whole family sleeps in this room at night. High humidity levels at the end of the evaluation period were caused by rain (Fig. 7).

Comfort assessment

There are two basic approaches to the assessment of thermal comfort [12]. The “rational index” approach is based on the response of subjects placed in climate-controlled chambers and is the basis of the ISO 7730 and ASHRAE 55 Standards. Some studies, e.g. Ref. [13] have found that this approach does not describe comfortable conditions adequately, particularly in naturally ventilated buildings. This inadequacy has led to the other “adaptive” approach, which is based on the premise that a subject is an active agent in any given thermal environment and that there is some thermal adaptation. Thermal comfort has been shown to be a function of the mean monthly outdoor temperature for the location and various algorithms have been suggested for calculating the “comfort” or neutral temperature, e.g. Ref. [14].

Perceptions of comfort vary. The longitudinal study of Ref. [15] of subjects in five climatic zones of Pakistan demonstrates this difference in perception. The winter comfort temperatures vary by 5.3 °C between the coldest and warmest zones. This study was conducted using city dwellers. Although Humla has a similar mean winter temperature to the two coldest Pakistani cities, the perceptions of comfort of Humli residents may not be the same. People in such isolated locations simply do not have a way of evaluating “comfort” in the same way as a person living in a city and this may lead to surprising results. As described earlier, previous researchers [11] studying other traditional people living in mountains of Nepal calculated a mean neutral temperature of 10.7 °C, which is over nine degrees lower than the coldest winter value determined by Ref. [15]. Despite the difficulty of comparing peoples’ perceptions of comfort, the authors know from their own experience of living and working in Humla that people do feel cold and that this effects their health and well-being.

The prime objective of this research was to obtain some understanding of the thermal behaviour of a typical Humli house in order to improve the internal conditions. Such improvements would complement the holistic community development programme of the local NGO (RIDS-Nepal). No such study has been conducted previously. The purpose of this work was not to assess people's feelings with respect to comfort or to derive a particular comfort temperature, but rather to use calculated comfort levels as an indicator of the effect of building envelope modifications. As cited earlier, some low-cost methods of improving the thermal performance of traditional Nepali houses have been suggested by Ref. [9]. In order to assess building envelope modifications, some readily derived indicator was required to assess their individual or collective impact on comfort.

An indication of the comfort levels experienced during the measurement period was determined using a commercially available thermal comfort prediction tool prepared for ASHRAE [16]. Although the tool contains eight thermal comfort models and calculates a number of indicators of thermal comfort, the "PMV-PPD" model was chosen to evaluate the conditions in the Humli house because its indicators are widely used and easily understood. The PMV (Predicted Mean Vote) index represents the sensation of a large population to a particular thermal environment. A PMV value represents the predicted vote on a seven-point thermal sensation scale. If the calculated value is within the range of −0.5 and +0.5, then the conditions are within the ISO (International Standards Organisation) comfort zone. The PPD (Predicted Percentage of Dissatisfaction) is a function of PMV and indicates the number of individuals likely to be unhappy with the conditions. This value never drops below 5% because of the assumption that there will always be a certain level of dissatisfaction, even if the PMV index is zero.

To use this tool, some assumptions were made because more input data was required than was measured in the Humli house. The mean radiant temperature (MRT) was assumed to be, on average, 0.2 °C higher than the air temperature. This assumption was based on the temperatures measured over a 10-day period in May 2007 at the HARS of RIDS-Nepal. The internal surface temperature of a rendered external stone wall and the room air temperature were measured on an hourly basis. The air velocity in Living Room 1 was measured using a hand-held hot wire anemometer (TSI Inc., VelociCalc Model No. 8350-1) in various positions and found to be low, i.e. in the range 0.0–0.1 m s^{-1}. The residents were assumed to be seated most of the time because the rooms are small and there is little room to carry out any other kind of activity. A MET value of 1.0, recommended for persons sitting quietly, was therefore used. Residents were asked about their clothing levels during the period of the study and the CLO calculator provided in the ASHRAE tool was used to calculate a value of 1.0. This was also assumed to be identical for all occupants, regardless of age and gender. Using the mean minimum db temperatures and their corresponding relative humidity (RH) values, PMV and PPD values were calculated with the comfort tool (Table 4).

Both PMV values were found to be outside the ISO comfort zone. At present, increasing the minimum temperature inside the house involves using the stove more often and this means using more fuel. For the poor in Simikot, obtaining fuelwood already involves significant labour and drudgery. For a 25 kg load, a family member must walk for 2 h, and then spend 1–2 h collecting the fuel. The return home walk with the fuelwood on their back takes 2.5 h, meaning over 5 h has been spent on this one task. If the family is lucky enough to own a smokeless stove, one 25 kg load will last approximately 2.5 days. If they are still using an open fire, one load will only last 1.5 days. In general, it is the women and children of the family who perform the arduous task of fuelwood collection and they must do it every other day. Purchasing fuelwood is simply not an option for the poor since it costs 250–300 NR or US$ 3–4 per 25 kg load.

Any appropriate strategy that might improve the comfort levels in a traditional Humli house therefore will have significant impacts. At an individual level, apart from a general improvement in well-being and health, less time would be spent on fuelwood collection. At a societal level, a reduced demand for fuelwood would ease pressure on dwindling supplies. In order to investigate possible options for comfort improvement, a TRNSYS thermal model of the Humli house was developed and validated, and that process is described in the later sections.

TRNSYS model

TRNSYS is a programme designed to simulate transient systems. It is the international benchmark software for predicting the performance of solar energy systems, but is also used extensively by researchers interested in building thermal performance. It is modular in nature and components of engineering systems are described in general terms as sub-routines. A model of a particular "system" is created by linking relevant sub-routines together and by supplying operational parameters specific to that system. In the case of the Humli house, the standard building sub-routine within TRNSYS (Type 56) has been used. Predictions of thermal performance were made on an hourly basis and measurements of air temperature and relative humidity within the house have been used to validate the model. This approach has allowed various strategies to improve the thermal performance of the house to be investigated.

The Type 56 sub-routine requires various fixed parameters to be supplied and assumptions to be made by the user. Table 5 indicates the material properties used. Other assumptions made in the model include: a fixed sky temperature=ambient air temperature less 12 °C, a ground reflectance=0.2 and a density of air=0.837. It was assumed that the house was occupied by the family and guests between 5 p.m. and 10 a.m. and that the four animals were housed in the stable between 7 p.m. and 7 a.m. Human activity levels in the house were assumed to be low, primarily for eating and sleeping, and therefore equivalent to “seated, at rest”, as defined in ISO 7730 within TRNSYS. The metabolic heat generation of an animal was assumed to be twice that of a human.

Model validation

In order to validate the TRNSYS greenhouse model, a climatic data file of total solar radiation, outside ambient temperature and relative humidity was constructed. These data were measured at a weather station (Spectrum Technologies Inc., WatchDog Model ET900), which is part of the long-term data collection system at the HARS. The mass of fuelwood used daily by the family was measured on a weighing scale at 6 a.m. every morning over 8 days (Table 6). The validation period was therefore from 27 March to 3 April, inclusively.

Indoor temperatures in the four rooms of the selected house were predicted on an hourly basis over the 8-day period and compared with measured temperatures. Fig. 8, Fig. 9, Fig. 10 and Fig. 11 show these comparisons for Living Room 1, Store Room 1, Living Room 2 and Store Room 2, respectively. Outside conditions, db temperature and relative humidity are also shown.

The main stove (Stove 1, Fig. 1) used by the family is located in Living Room 1 (Fig. 12). In the model, cooking was assumed to take place from 07:00 to 09:00 h in the morning and 18:30 to 20:30 h at night. The average value of fuelwood mass (Table 4) was assumed together with a fuel calorific value and stove efficiency of 15 MJ kg^{-1}[19] and 30%, respectively [20]. Heat output from the stove into the room was assumed be equally convective and radiative, based on average stove and wall temperatures of 100 and 15 °C, respectively. An air infiltration of three air changes per hour was assumed. The validity of this assumption was confirmed by measurements of airflow through a permanently open ceiling vent above the stove. The predicted maximum indoor air temperatures, as a result of stove use, generally occur at the same time as the measured peaks (Fig. 8). In approximately 50% of occasions, the predicted peak temperature is similar to the measurement, while peak temperatures are under-predicted in the remaining times.

The temperatures in Store Room 1 were found to be closely coupled to those in Living Room 1. Peak air temperatures in Store Room 1 were coincidental, but reduced in amplitude, with those in Living Room 1. Air exchange between these rooms was assumed to be 102 kg h^{-1}. A low airflow velocity of 0.1 ms^{-1} through a 0.34 m^2 gap between the two rooms would produce such a coupling. These assumptions produced acceptable predictions, compared to measured temperatures (Fig. 9).

There is a small inefficient fire place (Stove 2, Fig. 1) in the “verandah” area outside Living Room 2, which was evidently being used by visitors during the time of this research. No fuelwood consumption data was available, and therefore an estimate of 500 kJ h^{-1} was assumed to be the heat input by convection only. The stove was assumed to operate between the 05:00 and 05:30 h in the morning and 18:30 and 20:00 h in the evening. Air infiltration was assumed to be high in this room, i.e. 6 ACH^{-1} due to exposure and poor sealing. These assumptions produced good agreement between measured and predicted air temperatures in Living Room 2 (Fig. 10). The air exchange rate in Store Room 2 was assumed to be only 1.0 ACH^{-1}. Temperatures in this room appear to be largely determined by ambient conditions. Measured and predicted air temperatures compare well in terms of amplitude and time of occurrence (Fig. 11).

The air exchange rates used in the simulations of the four rooms are based on a combination of experimental measurements, and trial and error. These air exchange rates were fixed for the entire 8-day simulation period. In such traditional homes that are poorly sealed, one might expect that variations in local winds would be very influential in determining internal thermal conditions. In reality, the winds are quite predictable in this location. In the mornings, there is little or no wind, but in the afternoon the wind velocity increases to such an extent that it is considered too dangerous for aircraft to land or take off after midday. Despite this daily variation, acceptable agreement was achieved between the measured and predicted temperatures in each room using fixed values.

Performance improvements

The validated model has been used to investigate three strategies to improve the performance of the Humli house. These strategies were reducing infiltration, improving ceiling insulation and the creation of a "sunspace" in front of each living room. These strategies and their impact on comfort levels are described in more detail later.

Reduced infiltration

The validation modelling and some measurements with a hot wire anemometer indicated that air infiltration rates into the house are high. In Living Rooms 1 and 2, it was necessary to assume infiltration rates of 6 and 3 air changes per hour (ACH^{-1}) to produce reasonable agreement between measured and predicted internal dry bulb temperatures. Reducing these high rates of infiltration to the levels more commonly experienced in modern housing could be achieved by better construction and sealing methods. The effect of reduced infiltration rates was therefore investigated by reducing ACH^{-1} in both rooms to 1.5.

Improved insulation

The existing structure has a minimal level of insulation, which has been achieved using between 20 and 50 mm of bracken sandwiched between various roof layers. An improvement in comfort levels should occur if insulation levels are increased. These have been predicted by adding a 50 mm layer of insulating material on the inside surface of the ceilings in Living Rooms 1 and 2. The *R*-value of the insulation material was assumed to be 0.62 m^2 K W^{-1}, similar to that for 50 mm thick compressed straw [21].

Sunspaces

The semi-enclosed area in front of the two living rooms has been created using loose-fitting heavy timber planks (Fig. 2). The space could be converted into a sunspace, achieved by replacing the timber planks with a semi-glazed wall and door. A heavy-duty flexible ultraviolet (UV)-stabilised plastic sheeting would be used for the glazing to ensure longevity and to permit easy opening (by rolling up) in the event of overheating. This conversion would allow heat generated by absorbed solar radiation to be captured and transferred to the living rooms. Infiltration rates were reduced to 1.0 ACH^{-1} in the two living rooms because of the sunspace. Infiltration rates in the two sunspaces were set at 1.5 ACH^{-1} because it was assumed that improved sealing would be used compared to the original construction.

Sunspaces plus improved insulation

The combined effect of simultaneously improving insulation and creating two sunspaces has been investigated using the same parameters described in 9.2 and 9.3, but in combination.

Impact of improvement strategies on comfort levels

The model was used to predict the average minimum temperature and corresponding relative humidity levels in Living Rooms 1 and 2 in the existing condition and using the four strategies outlined above. These values, as well as the predicted PMV and PPD indicators, are compared with the same comfort indicators, calculated using the predictions of the validated model in the existing state (Table 7 and Table 8).

In both living rooms, reducing the (assumed) high infiltration levels is more effective than increasing the ceiling insulation levels. The model predicts that average temperatures in Living Room 1 increase by 0.8 °C with the former strategy, but only 0.3 °C with the latter, compared to predictions in the existing state. Changes in the PMV and PPD reflect the effect of these improvements. Conversion of the semi-enclosed area in front of each of the living rooms into a sunspace is the most effective single strategy to raise comfort levels. A sunspace not only transfers heat to the living rooms but also reduces the outside air infiltration rate into these rooms. Model predictions of the average temperatures in Living Rooms 1 and 2 are increased by 1.7 and 2.3 °C, respectively with this strategy, compared to predictions in the existing state. As expected, increasing the amount of insulation in the ceilings at all three levels in combination with a sunspace produces the greatest improvement in overall thermal conditions. The average temperature rises between 2.2 and 2.5 °C with the combined strategy.

Reducing the rate of infiltration of outside air, however, increases the inside relative humidity level. In the case of Living Room 2, the model predicts that the relative humidity reaches the saturation level. In practice, this would be unacceptable. However, Tables 7 and 8 indicate that the model over-predicts the average relative humidity levels in both living rooms, so in practice the saturation levels predicted are also likely to be an over-prediction. The reason for the over-prediction of relative humidity by the model is not clear and requires further investigation. Although more accurate (i.e. lower) relative humidity predictions will result in a rise in the values of PPD at the average dry bulb temperatures measured in this study, the relativity of the results is unlikely to change.

Conclusions

The thermal conditions in a traditional house in Simikot, the main town of Humla Province in northwest Nepal, have been investigated. Minimum ambient conditions inside the house in early April indicate that comfort levels are far below what is internationally recognised as acceptable. In the main winter months (November–February), average indoor temperatures will be significantly lower because of colder outside ambient temperatures, so corresponding comfort levels will be much worse in winter. Any strategy that raises comfort levels is likely to be beneficial in terms of general health and well-being, and possibly even to result in reduced fuelwood consumption.

The thermal performance of the house has been predicted using the thermal simulation programme TRNSYS. The model has been validated using temperature and fuelwood consumption data gathered over a 12- and 8-day period, respectively. An acceptable level of agreement between measured and predicted temperatures in four rooms of the house was achieved. The model indicated that high infiltration rates of outside air were likely to occur in the two principal living rooms. This finding was consistent with the poor level of construction, particularly sealing between adjacent building elements.

The validated model was used to investigate three separate strategies to reduce energy losses and thus improve thermal comfort conditions. Two of the strategies (reduced infiltration and additional ceiling insulation) are relatively low cost. Of these, reducing the level of infiltration of outside air was found to be more effective. A third strategy, which involved converting the existing semi-enclosed areas in front of each living room into a sunspace, would be more costly and time-consuming. However, it is not considered to be practically or financially impossible, particularly if low cost UV-stabilized plastic film were used as the glazing. To confirm that the idea would be culturally acceptable would require further investigation. The benefits of sunspaces in terms of increased average air temperatures were significantly higher than the other two strategies. As expected, a combination of all three strategies achieved the best results.

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Table 1. Summary of climatic data collected at HARS between May 2004 and March 2007

Month	Average monthly horizontal solar radiation ($MJ/m^2/d$)	Average monthly ambient temperature (°C)	Average monthly maximum ambient temperature (°C)	Average monthly minimum ambient temperature (°C)
January (82)	12.6	6.6	13.2	−1.4
February (55)	14	6.6	14.5	1.2
March (79)	17.4	8.1	15.4	2.5
April (44)	20.1	11.5	17.8	6
May (93)	19	14.5	20	9.4
June (90)	17.2	17.1	22.6	12.3
July (93)	14.9	17.9	22.5	14.9
August (77)	14.7	17.2	22.2	14
September (57)	17.7	16.8	22.6	12.4
October (39)	16.7	12.4	19.5	6.4
November (42)	14.2	8.5	17.4	1.1
December (93)	12.1	7.4	16	1.1

Figures in parentheses indicate number of days of complete data.

Table 2. Principal dimensions of the rooms in the Humli house

Room	Area (m^2)	Height (m)
Living Room 1	15.8	1.81
Store Room 1	5.8	1.81
Living Room 2	3.4	2
Store Room 2	4.2	2
Animal stable	27.9	1.9

Table 3. Summary of temperature and relative humidity in two living rooms

Conditions	**Temperature (°C)**	**RH (%)**	**Temperature (°C)**	**RH (%)**	**Temperature (°C)**	**RH (%)**
Average	21.2	33	16.2	33	11.9	42
Maximum	31.9	47	21.7	59	22.5	99
Minimum	14.9	23	10.6	24	3.3	21

Table 4. PMV and PPD values in two living rooms at occurrence of average minimum db temperatures

	Living Room 1				**Living Room 2**			
Condition	**Temperature (°C)**	**RH (%)**	**PMV**	**PPD (%)**	**Temperature (°C)**	**RH (%)**	**PMV**	**PPD (%)**
Mean minimum	17.3	31	−1.68	61	12.9	33	−2.88	98

Table 5. Material properties used in TRNSYS simulations

Material	Density (kg m^{-3})	Conductivity (W m^{-1} K^{-1})	Specific heat (kJ kg^{-1} $°C^{-1}$)	Reference
Granite	2640	3	0.82	[17]
Earth	1900	3.6	0.23	[18]
Timber	700	1.4	2.6	[17]

Table 6. Daily firewood use (kg) in Humli house over 8-day period

Date	**Morning**	**Evening**
27 March 2007	4.0	4.5
28 March 2007	4.0	6.0
29 March 2007	4.0	4.0
30 March 2007	5.0	4.0
31 March 2007	4.5	5.0
1 April 2007	4.0	5.0
2 April 2007	6.0	4.0
3 April 2007	5.0	4.0
Average	4.6	4.6

Table 7. Predicted impact of strategies to improve comfort levels in Living Room 1

Strategy	**Average temperature (°C)**	**Average RH (%)**	**PMV**	**PPD (%)**
Existing (measured)	17.3	31	−1.68	62
Existing (predicted)	16.9	54	−1.68	61
Reduced infiltration	17.7	67	−1.43	47
Improved insulation	17.2	53	−1.64	58
Sunspace	18.6	73	−1.26	38
Sunspace plus improved insulation	19.1	72	−1.01	27

Table 8. Predicted impact of strategies to improve comfort levels in Living Room 2

Strategy	**Average temperature (°C)**	**Average RH (%)**	**PMV**	**PPD (%)**
Existing (measured)	12.9	33	−2.88	98
Existing (predicted)	13.9	65	−2.48	93
Reduced infiltration	15.1	100	−2.00	77
Improved insulation	14.1	64	−2.43	92
Sunspace	16.2	100	−1.91	72
Sunspace plus improved insulation	16.4	100	−1.62	58

Fig. 1. Floor plans of three-level traditional Humli house.

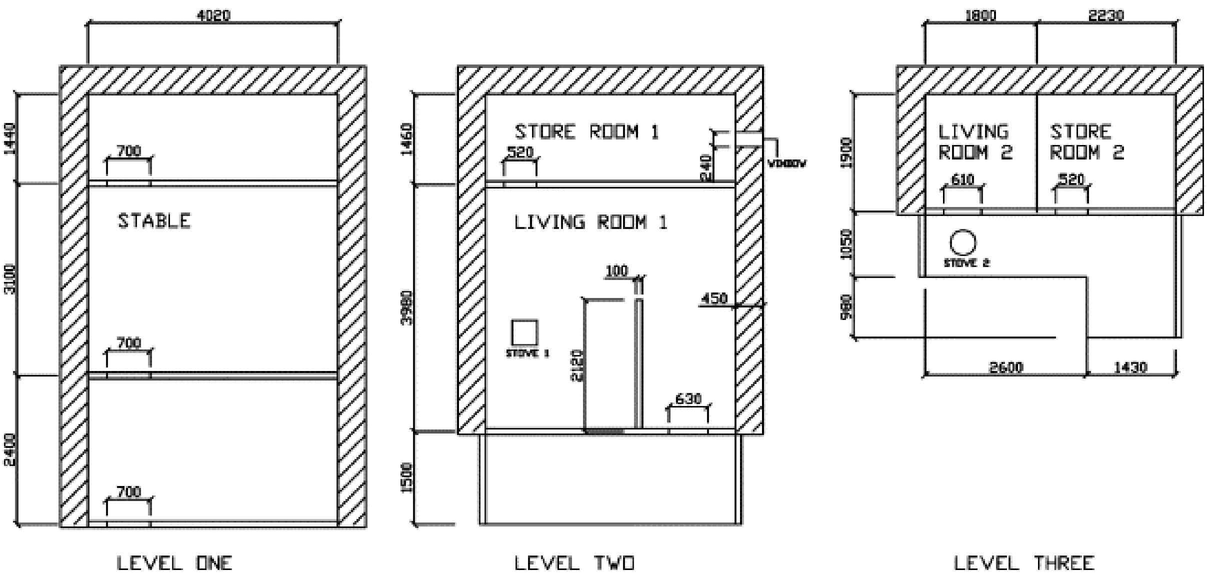

Fig. 2. Loose-fitting timber is used to create semi-enclosed area in front of rooms on top level of Humli house. (*Note*: end of stove flue in foreground.)

Fig. 3. Traditional Humli housing

Fig. 4. View of Level 1, showing mud roof and exposed wall.

Fig. 5. East side of studied house.

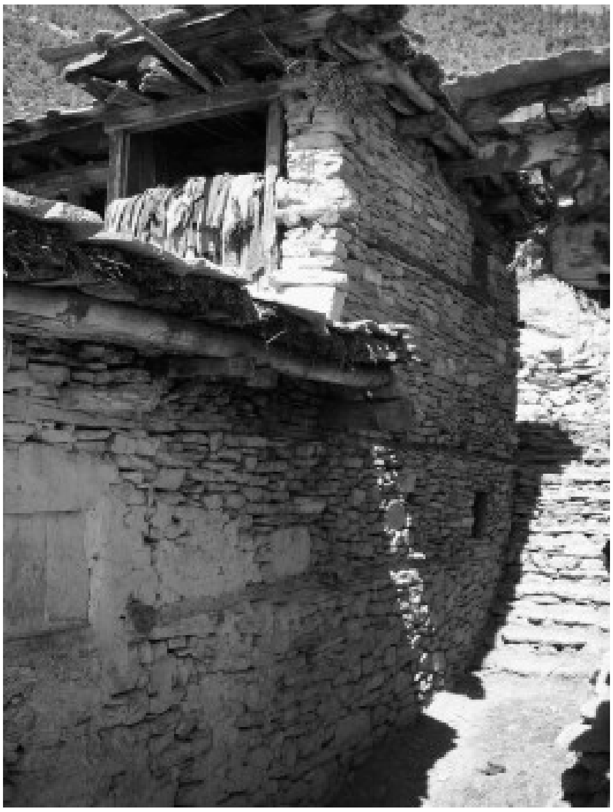

Fig. 6. Dry bulb temperatures inside living rooms of Humli house in early April.

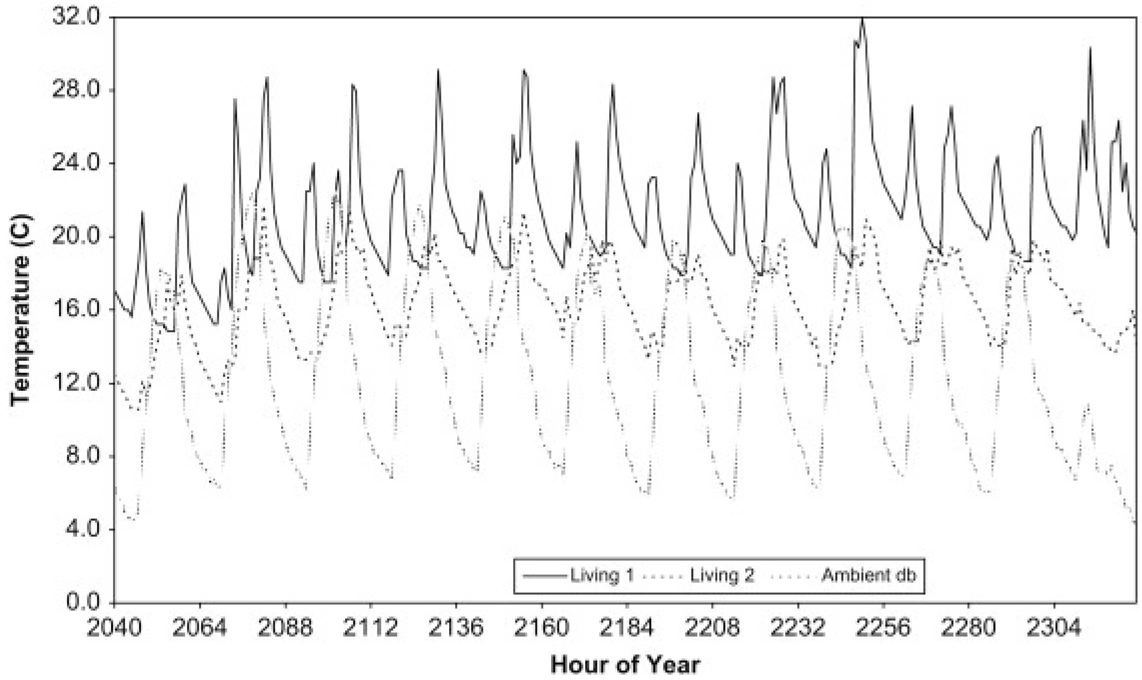

Fig. 7. Relative humidity levels inside living rooms of Humli house in early April.

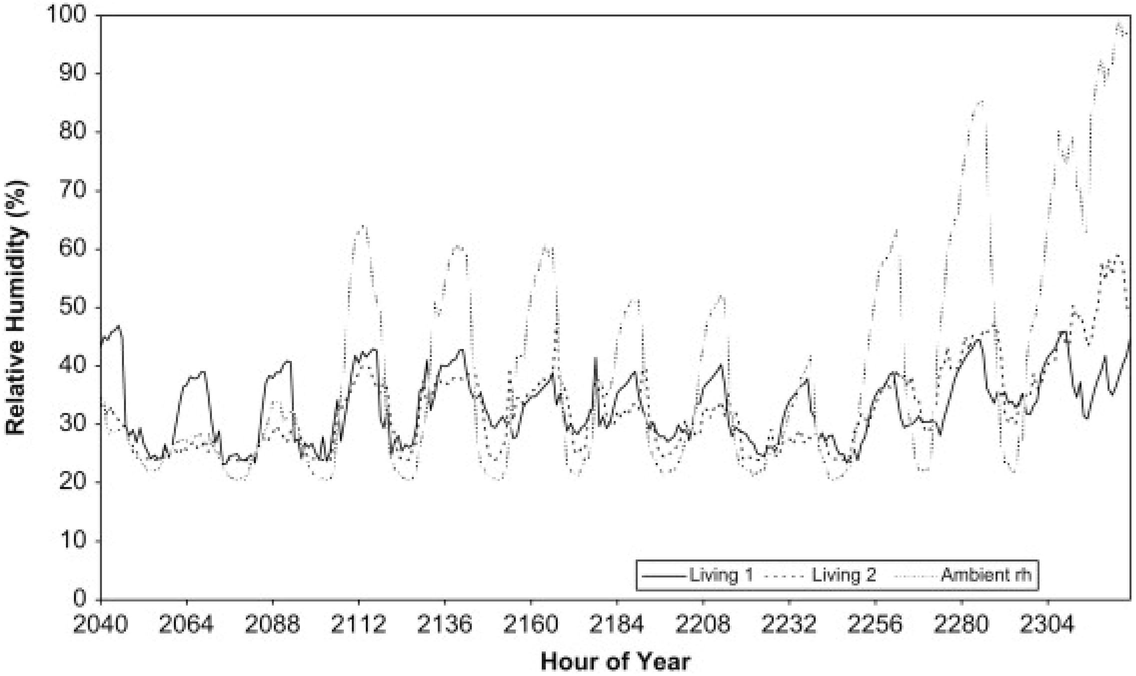

Fig. 8. Comparison of measured and predicted temperatures in Living Room 1 during 8-day period.

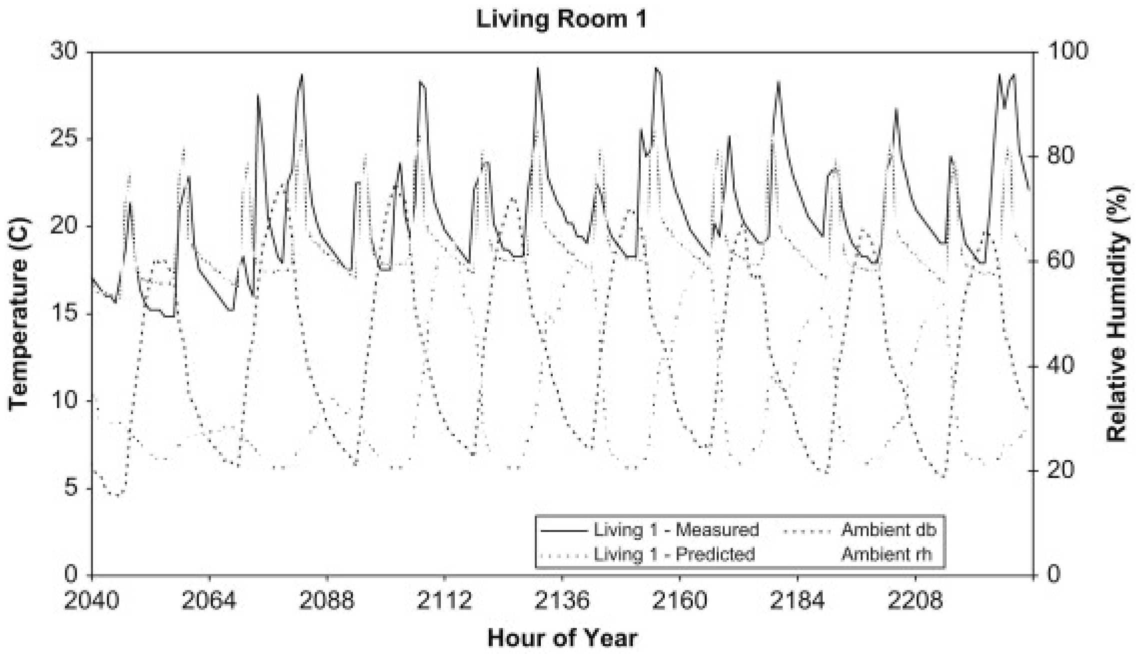

Fig. 9. Comparison of measured and predicted temperatures in Store Room 1 during 8-day period.

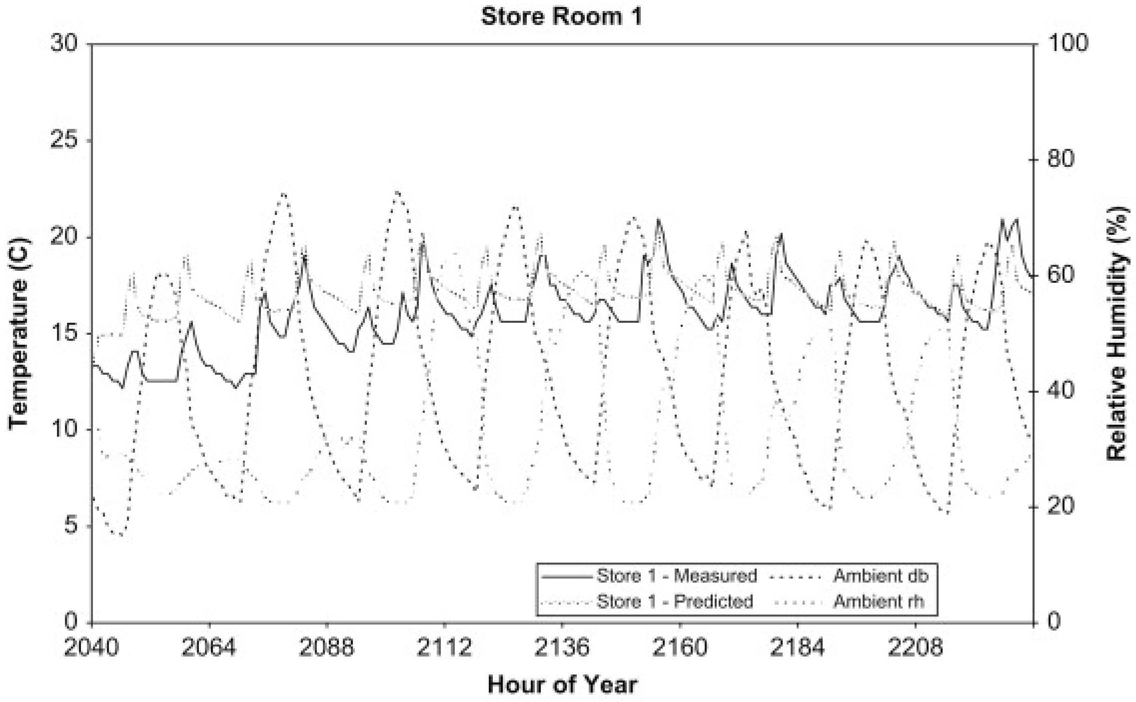

Fig. 10. Comparison of measured and predicted temperatures in Living Room 2 during 8-day period.

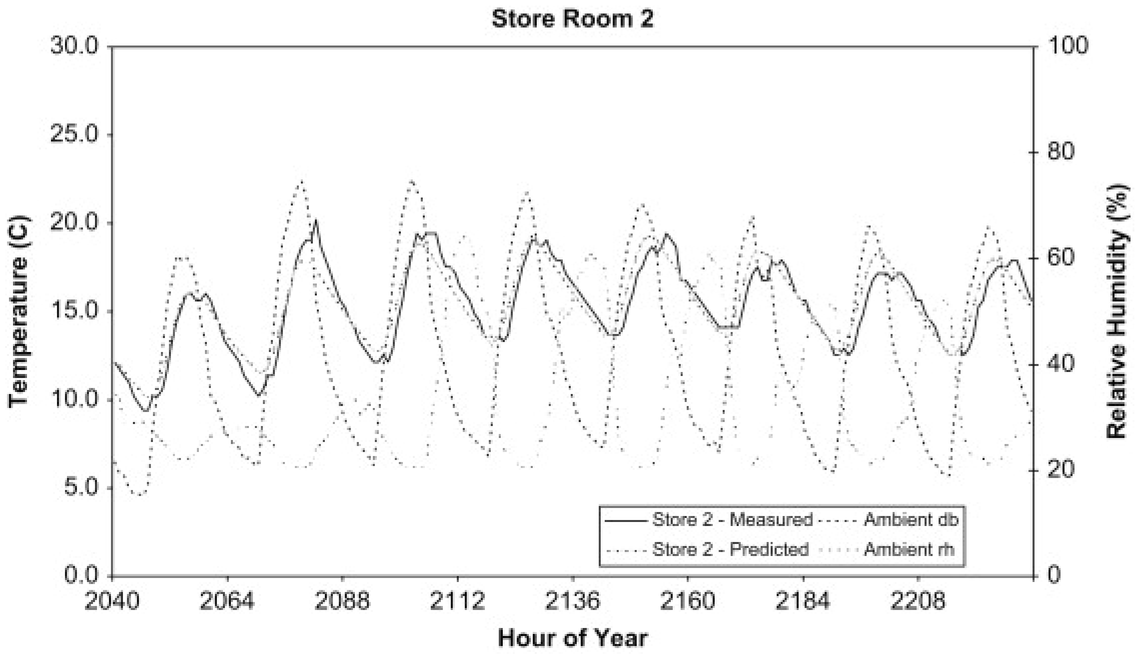

Fig. 11. Comparison of measured and predicted temperatures in Store Room 2 during 8-day period.

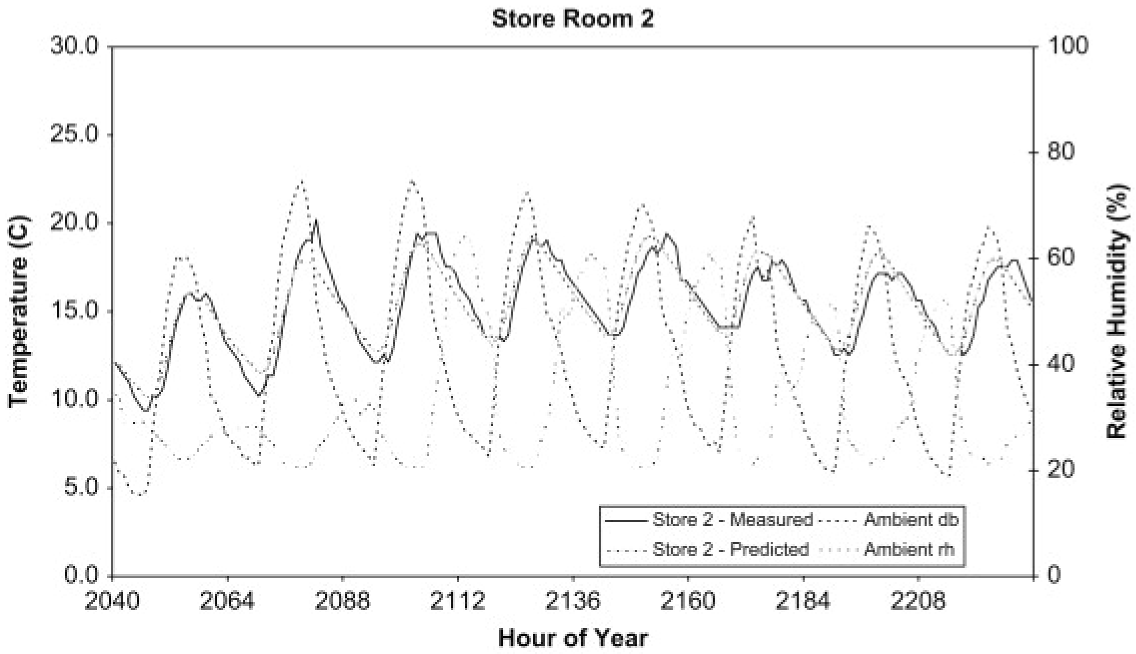

Fig. 12. Typical smokeless metal stove installed in Humli houses.