Effect of Air Infiltration Rate on Energy Consumption of a Residential Building in Bebena, Thimphu

Chimi Wangmo, Dawa, Dhendup Dorji & Neelam Monger

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Abstract

Energy consumption in buildings has been a major concern in the present construction field and the parameters that affect its performance should be carefully studied. Building airtightnessis an important contributing factor to the energy consumption of a building. The measurement of air infiltration is widely practiced in some countries of Europe and North America. However,this practice is still rare and uncommon in Bhutan. At present, traditional dwellings of Bhutanhave been found to be very leaky as compared to the modern Reinforced concrete structure (RCC) buildings mainly due to construction materials and techniques. The paper consists of air infiltration test carried out by the blower door method at a residential building in Bebena, Thimphu. The test has been followed by a series of data collection and interpretation of the readings obtained on site. The result obtained was air movement of 11.9^{-h} through the buildingenvelope which was satisfactory as in the case of Bhutan but was found to be exceeding the international standard of 3.0^{-h} in accordance to ISO 9972:2015. The average air movement of residential buildings in Bhutan is 11.7^{-h} according to the energy baseline report.

Key words – *air tightness, blower door test, air infiltration, building envelope*

Introduction

Building envelope plays a major role in the consideration of air tightness and in energy consumption of the building as a whole. The consequences of air leakages results in increasedenergy use, reduced thermal comfort and reduced air quality (Sandberg et al., 2007). The airtightness of a space is an important factor that is directly related to energy efficiency and proper ventilation. Resistance to the flow of air through unintentional opening and through cracks is called as air tightness (Berge, 2011). The airtightness can be determined usually through the amount of air leakage. While improving the air tightness can reduce the amount ofinfiltration/exfiltration through an envelope, the indoor air quality may be compromised as thecirculations of fresh air also depends on factors such as infiltrations. Airtightness can depend on many factors such as construction techniques, construction technology, architectural construction, building materials and so on. A common method to calculate this certain amountof air leakage is carried out through fan pressurization test or also commonly known as blower door (CEN, 2000). The blower door test is an accepted test method used internationally to calculate the amount of air leakage in a certain unit and hence corrective measures can be applied for retrofitting. It includes a calibrated fan, a manometer and a pressure sensing device.

In France, the air infiltration losses calculated additional 15% of total energy consumption in winter (Leprince and Lyon, 2011). In the USA, 33% of the heating loads was due to infiltrationsin office buildings (Emmerich, et al., 2005). In traditional Bhutanese structure, air leakages arefound to be more in comparison to other modern buildings due to air leakage through probableair gaps in wood joineries of rabsel, windows, doors and traditional walls of rammed earth and mud masonry(Jentsch et al., 2017). Jentsch and group (2017) tested airtightness of 50 buildingsin Bhutan. The worst performing buildings were those with conventional materials and construction methods with n_{50}= 75.5h^{-1} and buildings with n_{50}= 55.8 h^{-1} using natural dressed stone. The best performing building obtained the results that is nearly four times higher at n_{50}=11.7 h^{-1}. This is also higher than the value of 7.5 h^{-1} for a leaky detached house given in EN 15242:2007 and indicates that the values calculated in Bhutan's field study greatly surpassthose for both new and existing buildings in Europe. The measurement of air infiltration in traditional dwellings therefore prove to be challenging due to huge air exchange under depressurized conditions of 50Pa when tested by the blower door method.

Alfano and group (2012) tested airtightness of 20 residential buildings in southern Italy and found out that the Air change per Hour (ACH) or the n_{50} value was high. The natural ventilationsystem and the openings through the chimneys were the common causes of over ventilation. Kalamees2006) conducted air tightness test in 32 detached houses in Estonia. The air leakage pathways were detected using the thermal infrared camera and the smoke detector device. Then_{50} value was 4.9^{-h}. Alfano et al tested three buildings for airtightness in the Mediterranean region before and after retrofitting a window. The results obtained for air infiltration were comparatively low after the retrofitting. Rubber seals on window frames and high-performancewindows was substituted with the existing windows.

Air infiltration is a nonlinear phenomenon that depends on the building envelope's air leakageand climate driving forces of wind and temperature differential indoors and outdoors (Ren andChen, 2015). The need for determination of air tightness in buildings has been given emphasisdue its capability to reduce energy consumption and save money.

Table 1: Symbols

Symbol	**Quantity**	**Unit**
AE	Envelope Area	m^2
AF	Floor Area	m^2
Cenv	Air flow coefficient	$m^3/(h \cdot Pa^n)$
CL	Air leakage coefficient	$m^3/(h \cdot Pa^n)$
n50	Air change rate (ACH) at 50 pascals	h^{-1}
qenv	Air flow rate through the building envelope	m^3/h
qm	Measured air flow rate	m^3/h
qr	Readings of air flow rate	m^3/h
Δp	Induced pressure difference	Pa
V	Internal volume	m^3

CFM50	Air change in cubic feet per minute at 50 Pa	$ft^3\ min^{-1}$
n	Airflow exponent	$0.5<n<1$
ELA	Effective leakage area	cm^2
ρ	Air density	Kg/m^3
R	Specific gas constant	-
T	Temperature	°C

According to literature study, the results obtained from the tests provide parameters for air leakages through envelopes which can be used for the performance assessment of the building.The results can also assist the policy makers and relevant designers in making well informed decisions and reduce the overall energy consumption of the building.

The aim of this paper is to measure the air tightness of typical residential building in Thimphuto determine the energy consumption of the building with the blower door method. The resultsobtained for air tightness that can be analyzed in the decision-making for the retrofitting processin the residential unit. Appropriate relation of the infiltration rate in energy consumption can be derived for possible comparison with international standards. Effective methods required to maintain an optimal air flow rate in the residential unit would then be made possible through design interventions.

Method

For the preparation of the fan pressurization test, certain building parameters and environmentconditions need to be taken account of as this can affect the working of the equipment. Two internationally accepted method exists for carrying out the test. Method A is carried out in normal conditions where the intentional openings (exhaust fan) are not sealed and in Method B, the intentional openings are sealed during the test process. Method B was applied for the test (ISO, 2006).

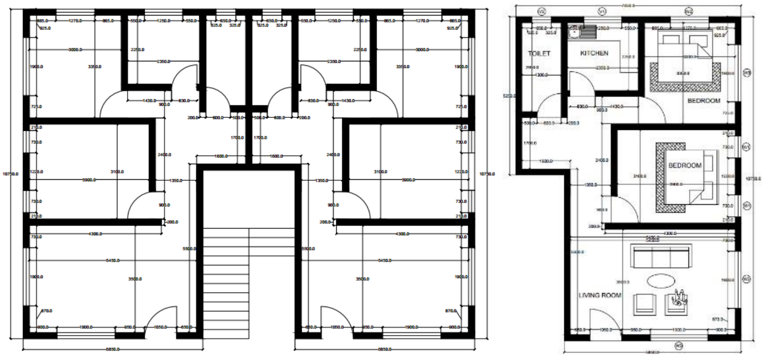

Figure 1: Ground floor (left) & Right-wing unit (right)

Site and building selection

The 2bhk residential building was located in Bebena, Thimphu with coordinates27°27’27.324’’N,89°37’22.8576’’E https://www.latlong.net/. The blower door test was carried out in only one unit which was located in the ground floor of the building with the exterior door of the unit directly exposed to the outdoor environment. The building material used was RCC with in situ concrete ground floors. The outer wall was constructed of normal brick walls with no insulation provided in the walls. The flooring for the living room was concrete flooring and timber flooring for the bedrooms. The intentional openings such as the exhaust fans were not provided in the kitchen.

Figure 2: Building location (left) & building view (right)

Table 2: Building parameters

Category	Specification	Category	Specification
Year built	2012	Number of Storeys	4
Age	7	Predominant wall material	RCC
Aenv	92.8	Energy Program	No
Afloor	52.7	Foundation Type	Isolated footing
V	149.2m^3	Ventilation Type	No
Local climate	Sub-tropical	Installation Layer	No

No mechanical ventilation and natural ventilation system existed in the tested unit. The fresh air for the unit was mainly supplied by air infiltration through the envelopes and the opening of the windows.

Environment conditions

The information from the instruments used for the measurement of the environment conditionsis shown below in Table. No 3. Almemo 2490, measuring instrument was used to check the temperature difference, pressure difference and the wind speed of the outside and inside environment. The parameter for wind speed was drawn from the Beaufort scale for wind forceindication. The DM 32-gauge manometer was used to calculate an average pressure baseline inside the room. The test carried out is in compliance with ISO 9972:2015. According to ISO9972:2015, the airtightness outputs will be valid when the test procedures fulfils the following requirements:

1. The wind speed near the ground does not exceed 3.0 m/s.
2. When determining the air flow coefficient C and air flow exponent n using a least squares technique, the correlation coefficient must be greater than 0.98 i.e., the value of r^2.
3. The air flow exponent should range between 0.5 and 1.0.

Table 3: Environment conditions

Category	Specification	
Wind speed:	2: Light breeze	
Operator Location:	Inside the building	(Depressurization)
Greatest Baseline Pressure Point	1.06 Pa	
Initial Bias Pressure:	0.47 Pa	
Final Bias Pressure:	0.33 Pa	
Average Bias Pressure:	0.4 Pa	
Initial Temperature:	indoors: 18.9 C	outdoors: 18.7 C
Final Temperature:	indoors: 18.9 C	outdoors: 18.7 C
Barometric Pressure	101.3 kPa	From Standard temp/pressure

Test Procedure

The blower door assembly can move air into the conditioned space or the unconditioned spaceat required fan pressure. The test was carried out in depressurization mode for this study. The setup of the house to be tested plays a crucial in obtaining valid results through the test. During the test, all the exterior opening was closed and the interior doors were kept open. Other than the equipment for the test, no other items were plugged in the socket. Trial test were carried out until the device read valid measurements. The air flow rate is defined by the power law with its relationship with pressure i.e.,

$$q_r = C_{env} (\Delta p)^n \quad (1a)$$

where, q_r is the air flow rate through the building envelope, C_{env} is the air flow coefficient and Δp is the induced pressure.

The air flow rate can be derived in relation to any given pressure (Walker et al., 1998).

Table 4: Comparison of the preparation method in this study to that in ISO 9972:2015

Classification of openings in windows	Method 1	Method 2	Method in this study
Ventilation openings for natural ventilation	closed	sealed	No such openings
Openings for whole building mechanicalventilation or air conditioning	sealed	sealed	No such openings
Openings for mechanical ventilation orair conditioning (only intermittent use)	closed	sealed	No such openings
Windows, doors, and trapdoors in envelope	closed	closed	closed
Openings not intended for ventilation	closed	sealed	

The intentional Calibrated door fan with varying range rings were replaced on the inlet side ofthe fan to artificially restrict the air flow with changing pressure, and thus controlling the fan pressure. The first set of readings were collected with the help of range B8, followed by B4 and finally B2 rings. The change in the rings were made as the air flow through the fan decreased. Ten readings at pressures between 10 and 60 Pa were taken for multipoint test. Thelocation of the air leakage pathways was first determined by manual assessment and then with the use of thermal infrared imager. The above-mentioned methods to located the air leakage for retrofitting is internationally accepted by energy auditors.

Figure 3: Range A, B8, B4, and B2 (left to right)

Results and Discussions

Test results show that the ACH_{50} of the unit under depresurization mode is 11.9^{-h}. This exhibited that the unit was leaky as compared to the internationa; standard of 3^{-}h.At present, Bhutan does not have any standards or limits to air-tightness of building envelopes. Therefore,the results obtained in the study was compared to international standards and requrements in other studies.

Table 5: Air change results

Specification	**Value**
Air changes at 50 Pa, n50 [/h]	11.93
Air flow at 50 Pa, [m^3/h]	1780.0
Air flow at 10 Pa, [m^3/h]	587.25
Air leakage coefficient, C_{env} [$m^3/h/Pa^n$]:	120.01
Air flow exponent, n	0.689
Coefficient of Determination, r^2	0.99944

The leakage area from the envelope i.e. the windows and the floors (reserved holes) are shownin table 5. Table 5. Shows that the leakage area is less through the window than the floor. Thereserved holes for the timber flooring had higher infiltration. The total leakage area is 542.5cm^2.

Table 6 Leakage results

Component	**Leakage**
Specific leakage rate (envelope) at 50 Pa, [$m^3/h/m^2$]	19.176
Specific leakage rate (floor) at 50 Pa, [$m^3/h/m^2$]	33.762
Effective leakage area at 50 Pa, [cm^2]	542.5
Specific effective leakage area (envelope) at 50 Pa, [cm^2/m^2]	5.8451
Specific effective leakage area (floor) at 50 Pa, [cm^2/m^2]	10.3

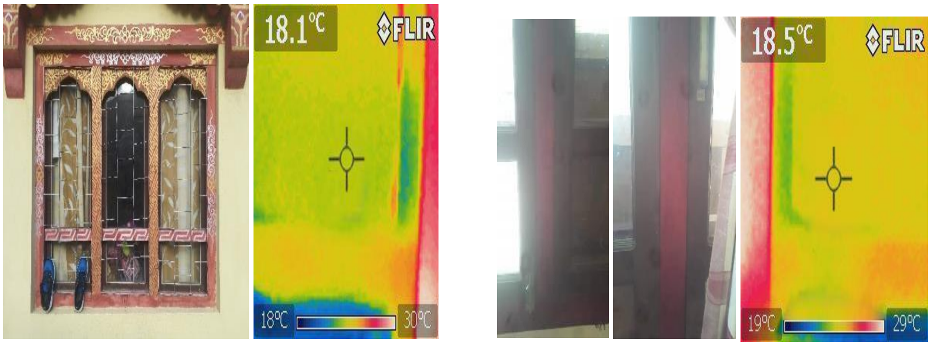

Figure 4: Leakage from window frames

The test results of the pressure-flow graph is shown in fig. 6. The flow versus induced pressuregraph indicates the volumetric air flow induced through the building envelope for a given pressure difference as a result of wind, temperature difference or mechanical forces.

The correlation coefficient measures how well the line of best-fit, fit the collected data of the test. While the graph exhibits valid results for the test, this ensures the accuracy of the data collected on site with least environmental pressure differences such as wind forces.

The specific leakage rate for both envelope and floor are derived by taking in the values for the air flow rate from theresults and the respective area for envelope and floor. The total effective leakage area of the tested unit as shown intable 6 is 542.5 cm2. The leakage area per m2 of the envelope and floor area is thenderived from dividing the effective leakage area from the envelope and floorarea.

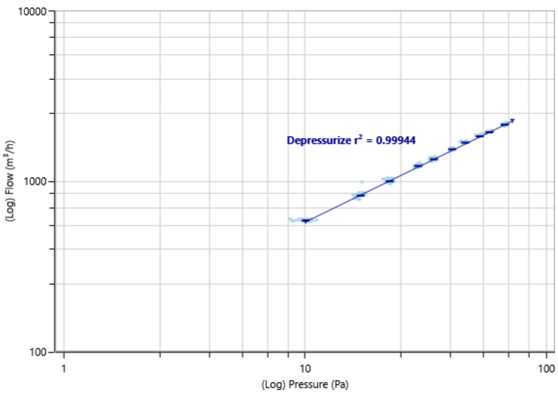

Figure 6: Pressure vs Air flow graph

Recommendation

Retrofitting of the interior space by detecting the probable leakages in the envelope and providing strategies to seal the leakages by use of sealants on windows and floors.

Estimated cost of air leakage

TECTITE uses the calculation procedure contained in ASHRAE Standard 136-1993 to estimate the average annual natural infiltration rate of the building. Annual heating cost =26 x HDD x fuel price x CFM50 x 0.6/N x Seasonal efficiency.

Table 7: Heating degree days

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Selected years	1999	2011	2005	2008	2008	2006	2007	2009	2007	1999	2001	2004
Average daily Tmin	−2.1	1.0	3.4	7.8	11.5	15.3	16.0	16.3	14.7	9.7	3.7	0.2
Average daily Tmax	15.3	17.4	20.0	22.6	25.3	26,8	27.1	27.6	26.2	22.7	19.6	16.3

Where, 26 is the result of multiplying the heat capacity of air (0.018) x 60 minutes x24 hours, HDD is the Heating Degree Days, Fuel price in BTU, N is the energy climate factor, Seasonalefficiency is the efficiency of heat source and 0.6 is the second correction factor.

Heating Degree days

Heating degree-days as shown in table no. 7 are derived on the basis of external dry bulb temperature information and in essence represent the sum of temperature differences to a base temperature over a defined period of time (CIBSE, 2006). Hereby the base temperature represents the daily mean external temperature below which the heating system would be considered as being operational in order to maintain a comfortable indoor climate (CIBSE, 2006; VDI 4710–2:2007). Heating degree days of Thimphu is calculated based on data from July 1995 to June 2014 from Simtokha weather station.

Table 8: Average HDD

Month	Jan	Feb	Mar	April	Oct	Nov	Dec
HDD	21.1	16.4	11.94	5.64	3.84	12.03	18.15

Months selected to represent a temperature reference year for the Thimphu valley on the basisof data from July 1995 to Ju ne 2014 from Simtokha weather station, also including the average daily minimum and maximum dry bulb temperatures of the respective months. (Data source: Department of Hydromet Services (DHMS), Bhutan.)

1. Average temperature for January = (Average daily T_{min} +Average daily T_{max})/2
2. According to ASHRAE Standard 136-1993 HDD is the annual base 65 F heating degree-days for the building location.
3. HDD for annually= 65° F - Average Temperature

Fuel Price

1Btu =0.293 W

According to 2017 Bhutan Electricity Authority, the approved value per unit is Nu. 2.07 inurban area.

Fuel price =0.293/1000 x 2.07Nu. =0.00061Nu.

N Value

The tested building was protected from three sides and it was considered as partially protected.The value of energy climate factor for partially protected building is 14.8 (ASHRAE Standard136-1993).

Seasonal efficiency

Seasonal energy efficiency of heater can be determined by Heating Seasonal Performance Factor (HSPF). HSPF is the ratio of BTU heat output over the heating season to watt-hours ofelectricity used.

The HSPF is related to the non-dimensional Coefficient of Performance (COP) for a heat pump, which measures the ratio of heat energy delivered to electrical energy supplied, independently of the units used to measure energy. The HSPF can be converted to a seasonally-averaged COP by converting both the BTU heat output and the electrical input to a common energy unit (e.g. joules). Since, 1 BTU = 1055.056 J, and 1 watt-hour = 3600 J, the seasonally-averaged COP is given by:

Avg COP = Heat transferred / electrical energy supplied = (HSPF * 1055.056 J/BTU) / (3600 J/watt-hour) = 0.29307111

HSPF. The heater that is used in the tested unit is the *Luxel NSB200.*

The annual heating cost =26 x HDD x fuel price x CFM50 x 0.6/N x Seasonal efficiency. Calculating the annual heating cost at ACH of 11.97 amounts to Nu. 1800.5

Figure 5: Luxel NSB 200

According to (ASHRAE Standard 136-1993) the desired value of air infiltration in residential building is 3ACH. Calculating the annual heating cost at ACH of 3 in the same method amounts to Nu. 452.78

With the air change value of 3ACH, there would be a total heat cost reduction of 74.8% of the building energy. This reduced energy would reduce the buildings energy consumption.

At 3 ACH, the air flow rate at 50 Pa results with a value of 447.6 m^3/h. Assuming that the unitis exposed to 3ACH the specific leakage rate for envelope and floor is 4.82 $m^3/h/m^2$ and 8.49 $m^3/h/m^2$ respectively.

At 11.93 ACH = 542.4 cm^2 (*Effective leakage area)*

For 3 ACH = $\frac{542.4}{11.93} \times 3 = 136.39\ cm^2$

The specific leakage area for envelope and floor at 3 ACH then calculates to 1.47 cm^2/m^2 and 2.59 cm^2/m^2. With the air change value of 3ACH, there is a total reduction of 74.85% of the specific effective leakage area in the unit. This reduced leakage area would reduce the air flowrate and hence reduce the overall energy consumption of the unit tested.

Design recommendation

During the test, the leakages were mostly observed in the envelopes i.e. mainly through the windows using the thermal imager. The leakage is commonly found out at the place where building envelope has two separate materials having two different properties, that is the joint between the window frame and the wall, which is often ignored. For cracks less than 1/4-inch wide, caulk is provided to fill the spaces around windows, doors, plumbing and pipes; and for larger cracks, expanding foam tape is used to tighten the gap. EPDM rubber (ethylenepropylene diene monomer rubber) sealants are used in the window frames to seal the air gaps. They are self-adhesive, inexpensive and easy to install. Air drafts through the bottom of the doors of the exterior facing door also contribute to the energy loss of the building unit. Door sweeps made of stainless steel with attached rubber strip are installed at the bottom to preventseepage of air.

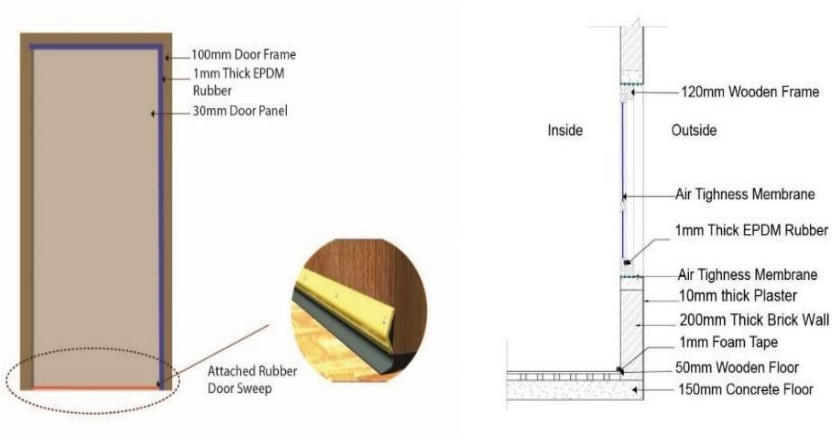

Figure 7 Window Section showing sealant

Estimated leakage area covered in windows

Considering the approximate width of air leakage to be 0.1 cm between the window frames,the sealants provided would cover an approximate area of:

W3=101.84 cm^2, $\mathbf{W_2}$ = 46.32 cm^2, $\mathbf{W_1}$ = 38.2 cm^2, $\mathbf{V_2}$ = 16.3 cm^2 and $\mathbf{V_1}$ = 39.32 cm^2

Total Area: $\boldsymbol{W_3 + W_2 + W_1 + V_1 + V_2}$= 101.84 + 46.32 + 38.2 + 39.32 + 16.3= 241.98 cm^2

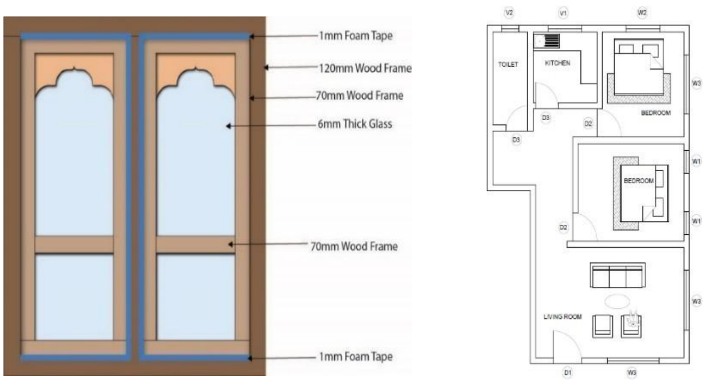

Figure 8: Elevation showing sealants (left) & location of specific windows

(right)

Therefore, the EPDM rubber sealants of 1mm thickness would reduce the area of the leakages by 44.61%. This indicates that the interventions proposed would be able to significantly reduce the air infiltration and energy consumption in buildings by provision of sealants to cover the air gaps between the window frames by about 45%.

Estimated leakage area covered in floor

Considering uniform leakage width of 0.1cm at the junction of floor and wall in the rooms with wooden flooring, the sealants provided would cover an approximate area of 131 cm^2 in Bedroom 1 and 140cm^2 in Bedroom 2. The values are derived by calculating the perimeter of the given space and the multiplying it with the leakage width of 0.1cm. The total leakage through the floor totals to 271cm^2. Therefore, the EPDM rubber sealants of 1mm thickness would reduce the area of the leakages by 49.9%. This indicates that the interventions proposed would be able to significantly reduce the air infiltration and energy consumption in buildings by about 50% through the floor. Therefore, the EPDM rubber sealants of 1mm thickness would reduce the area of the leakages by 44.61%. This indicates that the interventions proposed would be able to significantly reduce the air infiltration and energy consumption in buildings by provision of sealants to cover the air gaps between the window frames.

Conclusion

In this paper, the test for airtightness was investigated in Bebena, Thimphu. The total energy consumption at the infiltration rate of n_{50} value of 11.9 was calculated. A condition of the desired air infiltration was modelled by taking the standard ACH value of $3h^{-1}$ and calculating the total energy consumption due to heating demand annually. It was observed that 74.8 percentage of the energy savings could be achieved by controlling the air infiltration and through the effective leakage reduction of 74.85 percentage from the initial condition. ACH value of $3h^{-1}$ is internationally accepted (EN 13829:2000) infiltration rate and as compared to Bhutan's common ACH value of 11.7, the documented residential unit was found to have acceptable infiltration rate as per the construction practices commonly carried out in Bhutan but found to be leaky when compared to the international standards.

Despite the uncertainties involved in the detection of the real air leaks in the building, the leakages as observed during the field test with the help of the thermal imagers and manual assessment made the potential for improvement possible. Thus, the provision of sealants on theopenings to make the windows air tight is the most efficient and low-cost design intervention that can be provided to improve the current condition of the air infiltration. Provision of rubbersealants and foam tape in the windows and the edges of the timber flooring would reduce the leakage area as estimated, by 45% and 50% hence reducing the energy consumption of the building as a whole.

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About the authors

Chimi Wangmo, Dawa, and Dhendup Dorji are Architects currently working as free lancers in both design and construction industry in Bhutan.

Neelam Monger is an architect under the Ministry of Works and Human Settlement, Royal Government of Bhutan. They received their bachelor's degree in Architecture from the College of Science and Technology in 2020. Their shared interests include documentation and research of energy-efficient buildings, urban-rural settlements and vernacular architecture.