Research article

The potential for domestic thermal insulation retrofits on the South African Highveld

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Abstract

The South African Highveld is a portion on the inland plateau characterized by low winter ambient temperatures. Studies done in several climatic regions around the world have found a positive relationship between inadequate housing and low indoor temperatures during the winter season. Prolonged exposure to low indoor temperature is a threat to human physical health. This study characterizes indoor human thermal comfort conditions in typical low-income residential dwellings during the winter season. Mapping indoor human thermal comfort can assist in exploring the potential for domestic thermal insulation retrofits interventions. In-situ temperature measurements were done in 2014, 2016 and 2017 across three Highveld settlements of kwaZamokuhle, kwaDela, and Jouberton. The sample included a mixture of old (pre-1994), post 1994 Reconstruction and Development Programme (RDP) as well as non-RDP structures. Findings were that 88% of sampled dwellings in Jouberton 2016, 86% in Jouberton 2017, 62% in kwaDela and 58% in kwaZamokuhle had daily mean temperatures below the WHO guideline of 18°C. These low indoor temperatures indicate poor insulation in these sampled dwellings. Across all settlements, insulated dwellings had higher daily mean indoor temperatures than non-insulated dwellings. These findings indicate the potential to use thermal insulation retrofits in improving indoor thermal conditions as the majority of dwellings are non-insulated thereby exposing occupants to low indoor temperatures.

Keywords

Low-income, human indoor thermal comfort, ambient temperature, indoor temperature, solid fuels, retrofits, thermal insulation, inadequate housing

Introduction

Studies conducted in different climatic regions across the world have found a positive relationship between inadequate housing and poor indoor human thermal conditions (WHO, 2011). Wright et al., (2005), Summerfield et al., (2007) and Sakka et al., (2008) are some of the indoor human thermal comfort studies done in the European region. In South Africa one study by Naicker et al., (2017) was identified. The study focused on five low-income settlements in the city of Johannesburg. It was limited to summer months while this current study focuses on winter months. The current study fills the knowledge gap that exists in the field of human indoor thermal conditions during winter seasons. Human indoor thermal comfort is a subjective measure of peoples' satisfaction with indoor temperatures. It varies across cultures, individuals and geographical regions (Toe & Kubota, 2013; ASHRAE, 2010).

A successful house is one which is able to regulate indoor temperatures (Nicol and Humphreys, 2010). Inadequate housing has a profound negative impact on indoor human thermal comfort as well as increasing health risk exposure to occupants (Indraganti, 2010). Asthma, cross infections, respiratory infections, and excess winter mortality are some of the physical health threats that result from low indoor temperature exposure

(Anderson et al., 2012, Hui & Jie, 2014). In Europe alone, it is estimated that there are about one-quarter of a million winter deaths each year as a result of human low indoor temperature exposure (WHO, 2011). Furthermore, seasonal morbidity and mortality have been found to increase in low-income housing due to cold temperatures (Paravantis & Santamouris, 2015).

Thermally efficient housing is also a key element to dwelling energy consumption (Raja et al., 2001, Indraganti, 2010, Ponni & Baskar, 2015). Poor insulation hampers effective space heating in low-income dwellings. Indoor solid fuel burning for space heating remains a major source of household air pollution in South Africa (Nkosi et al., 2018).

Sites for this study are located on the South African Highveld where coal is abundantly used for space heating (Nkosi et al., 2017, Nkosi et al., 2018). Household coal burning causes degradation of both ambient and indoor air quality, thus posing a health risk to human beings (Smith et al., 2013, Language et al., 2016).

The purpose of this paper is to characterize indoor human thermal comfort environments of typical low-income residential dwellings on the South African Highveld during the winter season in accordance with WHO guidelines. Mapping indoor human thermal comfort can help establish the potential to use thermal insulation retrofits as an intervention strategy to improve low-income housing stock thermal performance. Section 2 discusses the materials and methodology used during the study.

Material and methods

Study area

Figure 1 represents the sampling sites where indoor temperature measurements were done. kwaZamokuhle and kwaDela are located in Mpumalanga province and fall under the Highveld Priority Area (HPA). The HPA is a region on the Highveld identified for high air pollution from both domestic and industrial sources. (Department of Environmental Affairs (DEA), 2011). Domestic solid fuel burning remains a significant source of fine particulate matter on the HPA (DEA, 2011). Jourbeton (located in North-West province) is situated on the Highveld region but is not under the priority area jurisdiction. Winters on the Highveld are mild and dry, but cold at night when frost may occur (DEA, 2011). Cold nights motivate households to use solid fuels for space heating contributing to the deterioration of both indoor and ambient air quality.

Instrumentation and data collection procedure

Indoor and ambient air temperature measurements were done using Thermochorn iButton DS1922L sensor loggers. In order to complement the study ambient air temperature measurements, extra data were obtained from the nearest South African Weather Service weather stations. (Jouberton, Klerksdorp station, kwaDela, Ermelo station and kwaZamokuhle, Ermelo station).

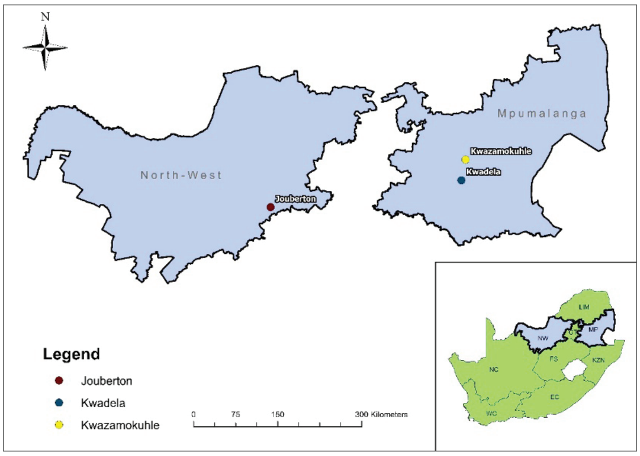


Figure 1: *Study sites in Mpumalanga and North West Provinces of South Africa*

Loggers were programmed to collect data over a 24hr period at 30-minute intervals. Monitoring periods are highlighted in Table 1. DS1922L sensors measure a temperature range of -40°C to +85°C at a resolution of ±0.5°C and are tested for accuracy in the laboratory by the manufacturer. Dwellings at each study site were disaggregated as follows; kwaDela winter survey - 13, Jouberton 2016 winter survey - 23, Jouberton 2017 winter survey - 8, and kwaZamokuhle winter survey– 24. Two winter surveys were done in Jouberton in 2016 and 2017 respectively in order to allow comparison over space and time. The sample included RDP government subsidy houses and non-RDP dwellings constructed pre-1994 and post 1994. The study used indoor temperatures as a proxy for determining indoor human thermal comfort levels while the relationship between ambient and indoor temperatures was used as a proxy for the level of thermal insulation.

Thermal comfort parameters

Indoor human thermal comfort is calculated using the following environmental parameters;

1. Indoor air temperature (*Ti*): Temperature surrounding the human occupants.
2. Outdoor Temperature (*To*): Average temperature of surfaces surrounding the occupant.

If indoor air temperature conditions correlate strongly with ambient temperatures, it becomes a good indicator of indoor personal exposure to occupants (Nguyen et al., 2014).

Location of temperature loggers

Indoor sensors were placed in the living room. The living room was chosen as a representative of the whole dwelling, assuming that occupants spend a considerable amount of time occupying this space. Indoor loggers were placed at approximately 1.5m above ground in accordance with ASHRAE 55-2005 and ISO 7730-2010 standards (Gallordo et al., 2016). This height was chosen in order to avoid human interruptions with the sensors.

Ambient sensors were deployed on the outside southern walls of a select number of dwellings across the settlements. The northern outside walls were avoided as these receive the majority of direct solar radiation during the day. Prolonged sensor direct sun exposure negatively influences measurements. The collected data were analysed on a daily basis for indoor variations throughout the monitoring period. Furthermore, indoor and ambient temperatures were correlated to gauge the influence of ambient temperature on the indoor temperature in order to establish the functionality of insulation material. Results of the study are discussed in section 3

Sampling was done in the winter months of June, July, and August as indicated in Table 1. These are the coldest times of the year on the South African Highveld. Winter indoor monitoring was chosen as this is the season where low-temperature exposure can be experienced.

Table 1: *Winter indoor temperature monitoring times*

Location	Year	Period	Insulated	Non-insulted	Total	Number of monitoring days
Jouberton	2017	1June - 5 July 2017	1	7	8	33
kwa-Zamokuhle	2017	17 July - 28 August 2017	10	14	24	40
Jouberton	2016	15 July - 23 August 2016	3	20	23	37
kwaDela	2014	10 July - 30 August 2014	5	8	13	19

Results

This section gives an account of the results and findings.

Indoor and ambient temperatures during the survey

Table 2 shows the daily instantaneous minimum, maximum temperature values for both indoor and ambient temperature during the surveys. The lowest ambient temperature across all study sites was recorded in Jourbeton 2017 at -3°C, while an ambient maximum of 27.5°C was recorded in Jourbeton during 2016. The lowest indoor temperature was recorded at -2°C in Jouberton in 2016 while the highest indoor temperature was recorded in kwaZamokuhle at 39°C.

Figure 2 shows daily mean indoor temperatures of all sampled dwellings for the three settlements comparing insulated and non-insulated structures. The trend established was that insulated dwellings had higher mean daily indoor temperatures than non-insulated structures across all settlements.

In kwaDela, the lowest daily mean indoor temperature recorded was 4°C in non-insulated dwellings while the highest temperature was 17°C. The lower quartile and upper quartile temperatures were 11°C and 13°C respectively giving an interquartile range of 2°C with a median temperature of 12.5°C. On the other hand, insulated structures had the lowest indoor temperature of 17°C with the highest temperature of 23°C. The recorded lower quartile and upper quartile temperatures were19°C and 22°C respectively giving an interquartile range of 3°C.while the median temperature was 20°C.

Table 2: *Daily minimum and maximum instantaneous indoor and ambient temperatures*

Location	Year	Minimum °C	Maximum °C
kwaDela (n=13)	2014		
Ambient		-2	22
Indoor		4	38
Jouberton (n=23)	2016		
Ambient		-1.3	27.5
Indoor		-2	36
Jouberton (n=8)	2017		
Ambient		-3	26.5
Indoor		0.5	31
kwaZamokuhle (n=24)	2017		
Ambient		-3	22
Indoor		-1	39

In Jouberton 2016, the lowest indoor daily mean temperature recorded was 11°C in non-insulated dwellings and the highest mean daily temperature being 19°C. The lower and upper quartile temperatures of 15°C and 17.5°C respectively were recorded giving an interquartile range of 2.5°C with a median temperature of 16°C. For insulated dwellings, the lowest temperature was recorded at 15°C and highest at 23°C. Lower quartile was 16°C with an upper quartile of 19°C giving an interquartile range of 3°C. The median temperature was 18°C.

From the Jourbeton 2017 survey, the lowest mean indoor temperature in non-insulated dwellings was 13°C with the highest temperature of 17.5°C. The lower quartile temperature was recorded at 15°C, while the upper quartile temperature was recorded at 16°C giving an interquartile range of 1°C with a median of 15.5°C. On the other hand in insulated dwellings, the lowest temperature was 16°C and highest at 21°C. The upper quartile temperature was 19.8°C with lower quartile temperature at 18.5°C giving an interquartile range of 1.3°C. The median temperature was 18.7°C.

In kwaZamokuhle 2017, the lowest and highest mean daily temperature in non-insulated dwellings recorded was 13°C and

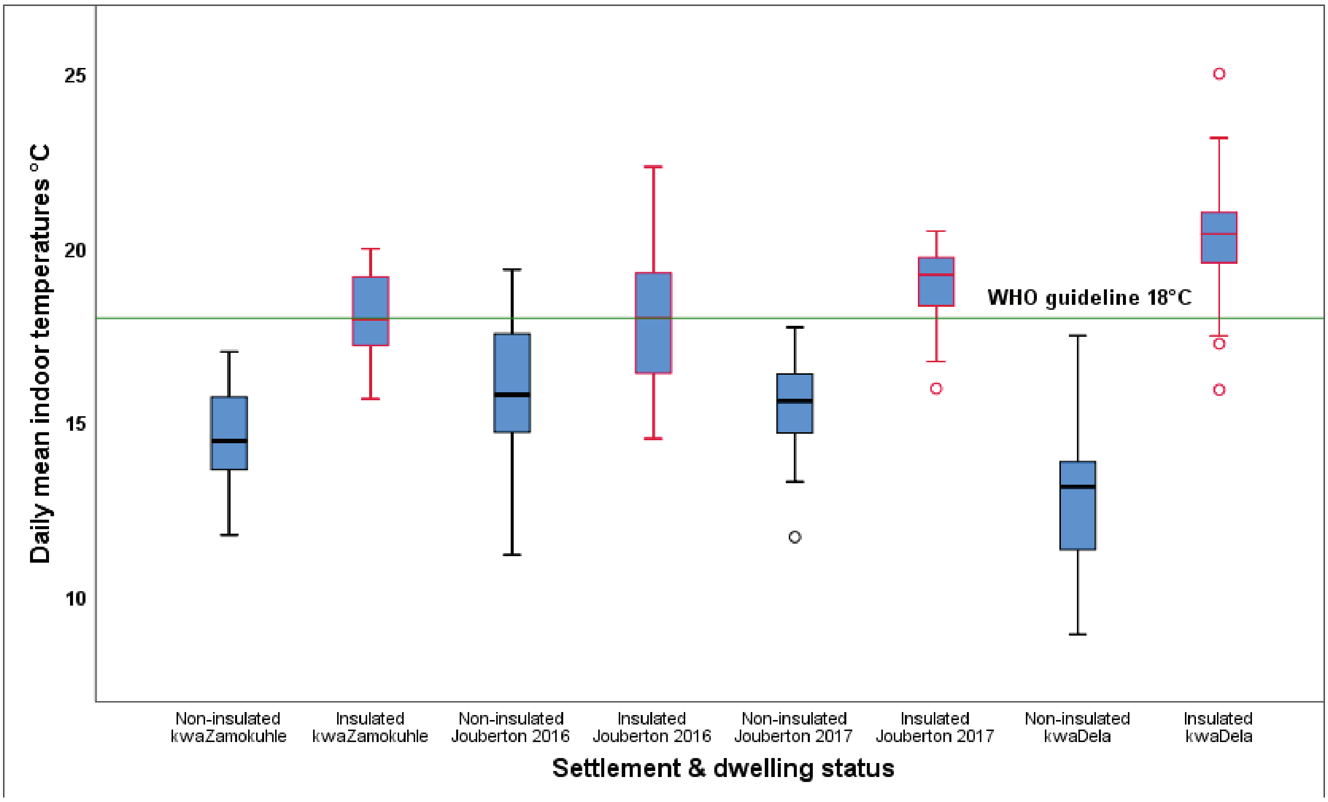


Figure 2: *Daily mean indoor temperatures across all settlements during the monitoring surveys*

17°C respectively. The upper quartile temperature recorded was 16°C and a lower quartile value of 14°C giving an interquartile range of 2°C. The median temperature was recorded at 14°C. The lowest temperature in insulated dwellings was observed at 16°C and highest temperature at 19°C. The upper quartile temperature was recorded at 19°C with a lower quartile of 17°C giving an interquartile range of 2°C. The median temperature was recorded at 18°C.

Table 3 shows a scatter plot representation of the indoor and ambient temperature relationship across the three settlements in non-insulated and insulated dwellings. For both surveys in Jouberton 2016 and 2017 non-insulated and insulated dwellings showed a strong positive correlation between ambient temperature and indoor temperature. Non insulated dwellings had a correlation of (r=0.61) and (r=0.65) for 2016 and 2017. Insulated dwellings also had strong positive correlation for both years of surveys (r=0.77) and (r=75) in 2016 and 2017 respectively.

In kwaDela, the ambient and the indoor temperature had a weak positive correlation relationship for both non-insulated and insulated dwellings. Non-insulated dwellings had a correlation of (r=0.10) while insulated dwellings had a correlation of (r=0.12).

In kwaZamokuhle, non-insulated dwellings showed a strong positive correlation between ambient and indoor temperature at (r=0.92) while a weak correlation was shown for insulated dwellings at (r=0.02).

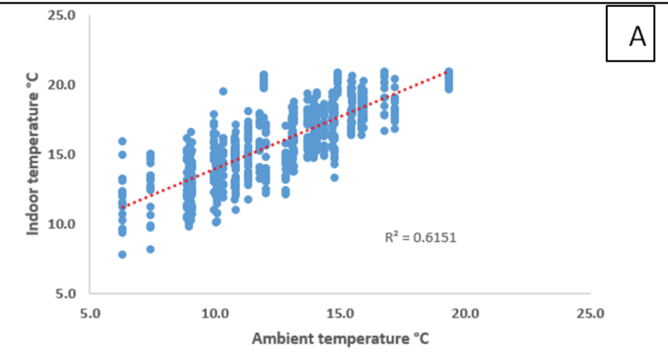
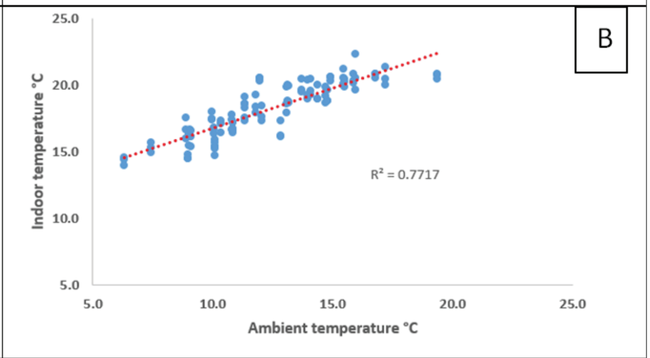
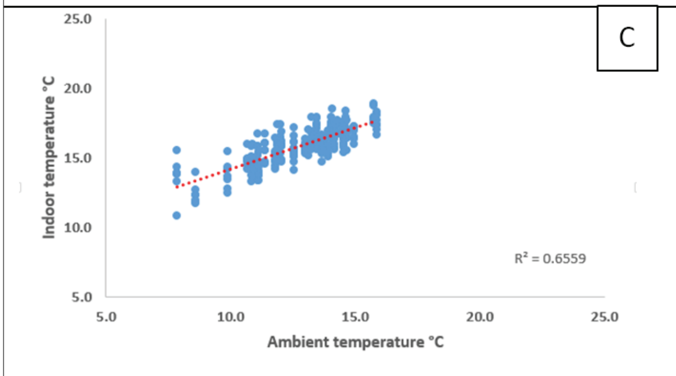
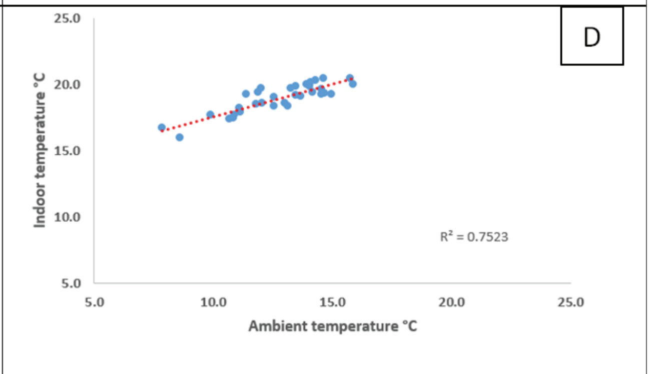
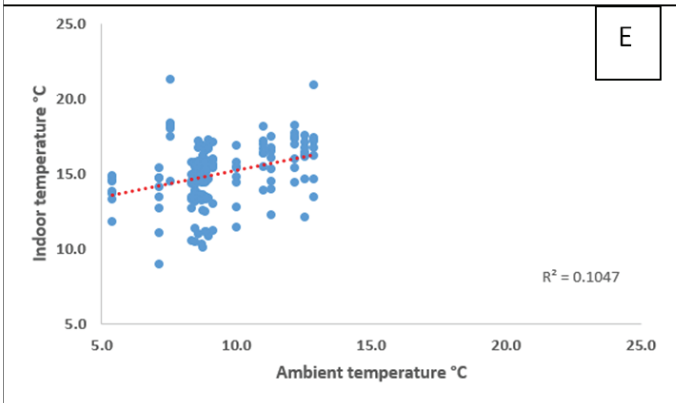
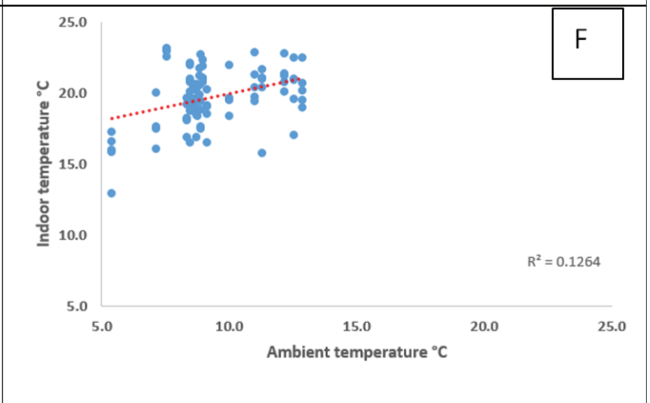
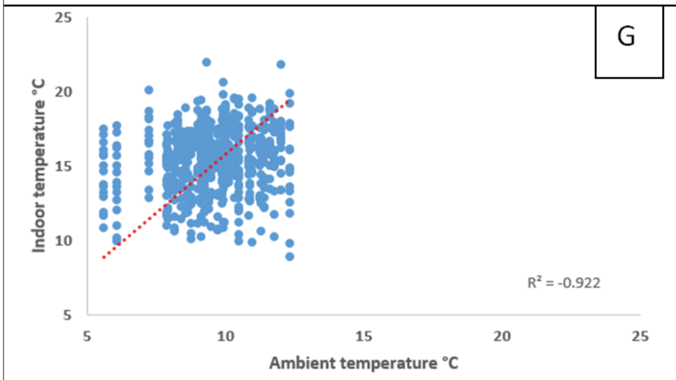
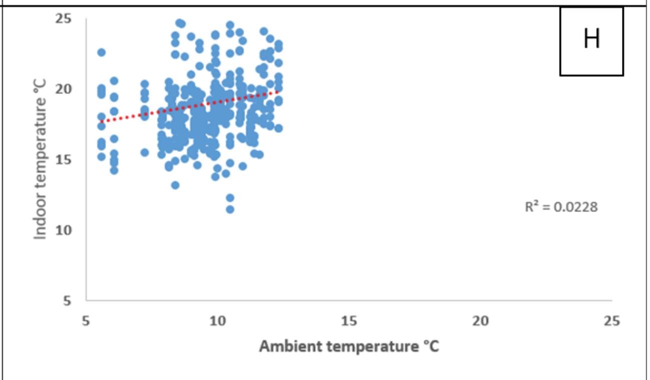
Table 4 shows the percentage representation of sampled dwellings which had mean daily indoor temperatures falling below the WHO guideline of 18°C throughout the monitoring period. The highest percentage of structures which fell below the 18°C minimum threshold was in Jourberton with 88% and 86% for 2016 and 2017 respectively. kwaZamokuhle had the least number of dwellings falling below the WHO minimum threshold of 18°C at 58% of the dwellings not meeting the prescribed guideline. From Table 3, it can be inferred that Jouberton structures are poorly insulated as compared to those in kwaDela and kwaZamokuhle.

Discussion

The study found that all non-insulated dwellings daily mean indoor temperatures fell below the WHO standard guideline of 18°C while insulated structures managed to maintain or were above 18°C. Furthermore, scatter plots correlations indicated that indoor temperature in kwaZamokuhle and Jouberton is strongly influenced by ambient temperature changes regardless of whether they are insulated or non-insulated. A comparison between insulated and non-insulated structures also found that insulated structures had warmer interiors than non-insulated at all times of the day. The ability of insulated structures to maintain higher indoor temperatures throughout the monitoring period can be attributed to their better capacity to retain internally generated heat as well as being able to retain solar heat gain during the day.

Indoor temperature recordings indicated that temperatures peaked during afternoon monitoring (10am-1pm). In free running buildings indoor temperatures are a consequence of heat gained

Table 3: *Scatter plot showing indoor and ambient temperature relationship for non-insulated and insulated dwellings*

Non-insulated	Insulated
	
	
	
	

***A**-non-insulated (Jouberton 2016)*
***B**-insulated (Jouberton 2016)*
***C**-insulated (Jouberton 2017)*
***D**-insulated (Jouberton 2017)*
***E**-non-insulated (kwaDela)*
***D**-insulated (Jouberton 2017)*
***G**-non-insulated (kwaZamokuhle)*
***H**-insulated (kwaZamokuhle)*

Table 4: *Percentage number of dwellings with daily mean indoor temperatures of < 18°C*

Site-survey	Total (n)	% < 18°C
Jouberton winter 2016	24	86
Jourbeton winter 2017	7	88
KwaZamokuhle winter 2017	26	58
kwaDela winter 2014	14	62

from solar heating (Yohanis and Mondol, 2010). On the other hand lowest indoor temperatures were recorded during early mornings (between 1am-6am). The trend was similar for both non-insulated and insulated dwellings. Differences were however noted that the insulated structures retained higher indoor temperatures at night times compared to non-insulated structures. This is can be attributed to that non-insulated structures tend to lose heat relatively faster as compared to insulated structures.

Subsidy government RDP structures built post-1994 are single brick walled and lack plaster making heat retention difficult (Naicker et al.,2017). Significantly, the study found that indoor temperatures for dwellings in Jouberton (2016)- 88%,Jouberton (2017)-86%, kwaDela-62% and kwaZamokuhle -58% experienced mean daily temperatures of less than 18°C throughout the monitoring period. Prolonged exposure to such indoor temperatures poses a threat to human thermal comfort and physical health wellbeing especially the elderly, children and others with underlying medical conditions.

Previous studies have confirmed that exposure to low indoor temperatures increases the risk of respiratory infections and asthma attacks. In Northern Ireland, Yohanis & Mondol (2010) found that at least 80% of monitored dwellings had winter internal temperatures ranging from 15-20°C. Alevizos et al., (2013) found that winter average indoor temperatures in Greece varied between 11.7°C and 21.11°C. Minimum indoor temperatures were found to be between 5.2°C and 18.1°C. Oreszcyn et al. (2006), monitored 1600 low-income houses in low-income dwellings of England and found median temperatures of 19.1°C in living rooms during the day. Two studies in Ireland and Switzerland estimated that home retrofitting resulted in energy savings as well as positive health outcomes for occupants (Chapman et al., 2007, Chapman et al., 2009).

The three mentioned studies focused on low-income households. These findings estimate high exposure levels to low indoor temperatures that occupants of low-income dwellings in Europe experience during winter seasons. It is important to note that even though similar findings were obtained in the European studies, climatic conditions differ to those of South Africa where winter ambient temperatures do not get as low as those experienced in Greece and Northern Ireland. The common element is that the poor are exposed to low indoor especially where their dwellings are not insulated. Prolonged low-indoor temperature exposure increases the risk of respiratory infections as well as other related ailments especially for the elderly and young children.

Findings from Jouberton and kwaZamokuhle are similar to Naicker et al., (2017), which reported that RDP dwellings in Bramscheville are highly sensitive to outside temperature changes during the summer season. These are structures similar to the majority of structures sampled in this study.

The main limitation in this study is that human indoor thermal comfort is also influenced by other environmental factors such as wind speed and human factors such as clothing, age, metabolic rates, and occupant ventilation behavior practices also influence thermal comfort which was not taken into account.

Conclusions

Out of the three sites located on the Highveld, 88% of dwellings in Jouberton in 2016, 86% in 2017, 64% in kwaDela and 61% in kwaZamokuhle of sampled dwellings had indoor temperatures of less than 18°C. Such low indoor temperatures expose occupants to human health risks such as respiratory infections and asthma attacks especially young children and the elderly.

High level of dwelling sensitiveness to low ambient temperature changes was particularly observed in Jouberton and kwaZamokuhle for both insulated and none-insulated structures. Dwellings in kwaDela had a weak correlation between ambient and indoor temperatures. Low indoor temperatures in non-insulated dwellings translate to households using more energy for space heating especially solid fuels that result in air quality deterioration. The study confirmed the value of insulation in improving indoor thermal conditions in residential housing as shown by the ability of sampled insulated dwellings to maintain comfortable indoor temperatures throughout the monitoring period, as spelled by WHO standards.

All through the monitoring period insulated dwellings had higher indoor temperatures hence achieving the WHO human indoor thermal comfort guidelines while uninsulated dwellings did not meet the WHO standards. These findings suggest that there is potential for thermal insulation retrofits interventions on the South African Highveld in order to improve the indoor thermal conditions of low-income dwellings housing stock. Retrofit interventions can reduce household reliance on solid fuels for space heating consequently reducing emissions as well as yielding physical health co-benefits for occupants.

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Author contributions

Newton R. Matandirotya wrote the manuscript with support from Dirk P. Cilliers and Roloef P.Burger. Christian Pauw and Stuart J. Piketh conceived the idea for the study as well as editing the report. Bridgette Language carried out the experiment for the study and edited the manuscript.

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