Energy & Buildings 264 (2022) 112035

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Comparing thermal performance of standard humanitarian tents

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ARTICLE INFO

Article history:
Received 18 November 2021
Revised 9 March 2022
Accepted 19 March 2022
Available online 22 March 2022

Keywords:
Humanitarian shelter
Humanitarian tents
Thermal performance
Thermal comfort
Temperature simulation

ABSTRACT

Humanitarian tents provide emergency shelter for people displaced by conflict and disaster in diverse climatic conditions. This article compares the thermal performance of two standard humanitarian tents – the Standard Family Tent (SFT) and the Geodesic Family Tent (GFT). The SFT is the most widely used humanitarian shelter, while the GFT was recently introduced as a potential replacement intended to provide, *inter-alia*, improved thermal performance. The study aims to assess the extent to which this intention is achieved and, in doing so, improve understanding about how tent material and morphology affect thermal performance. Several variables, including internal air temperature, surface temperature, relative humidity and air change rates, were measured and compared in hot and cold conditions. Results demonstrate that the GFT performs better than the SFT regarding radiant heat gain, conductive heat loss and increased air tightness. However, performance of the GFT in relation to heat gain and heat loss is similar to that of the SFT with an additional shade net. Other functional advantages of the GFT are improved structural stability and spaciousness, which, together with improved thermal performance, suggest this marginal innovation in shelter design can positively impact emergency shelter living conditions.

1. Introduction

Humanitarian tents are an important component of shelter assistance provided to people displaced by disaster or conflict. Tents are an effective form of emergency shelter, given that the potential for efficient packaging simplifies the logistics of distribution and that the relatively uncomplicated character of tents allows cost efficiency and enables rapid assembly without specialist skills or equipment. The Global Shelter Cluster, which coordinates the large number of humanitarian organisations providing shelter assistance internationally, estimates that 4.9 million people received shelter support in 2019 [21]. The United Nations High Commission for Refugees (UNHCR) distributed more than 240,000 emergency shelters in 2019 and 2020 [20]. These numbers highlight that each year humanitarian tents provide shelter for many people displaced by disaster and conflict.

While the precise insulating performances of tents vary, low thermal mass and resistance of fabrics entail a general limitation on insulating capabilities. Fabric tent envelopes are typically poor insulators against radiant and conductive heat gain in hot climates, and against conductive heat loss in cold climates [16]. This suggests that tents may provide adequate internal comfort in moderate climates only. Yet, humanitarian tents are used under diverse climatic conditions due to the varied geographic locations of disasters and conflicts as well as the prolonged period of *emergency* shelter – with the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) estimating that the average duration of humanitarian crises be more than nine years [14]. Thus, people may be accommodated in humanitarian tents across seasons in hot and cold climates.

In contrast with the varied conditions of emergency shelter, the design of humanitarian tents is standardised. The Standard Family Tent (SFT) is the predominant humanitarian tent design, due in part to its endorsement by two organisations that co-chair the Global Shelter Cluster - UNHCR and the International Federation of the Red Cross (IFRC). The materials of the SFT include a heavy polycotton envelope, rigid steel poles supporting the walls and central ridge, and a light polycotton inner lining [15]. The Geodesic Family Tent (GFT) is a relatively new humanitarian tent that was released in 2018 following a research and development process that involved IFRC, UNHCR and industry partners Alpinter SA, NRS Relief and Oxylane [6]. In relation to the SFT, the development of the GFT sought to: reduce weight, increase durability (in use and storage), improve insulation against heat and cold, increase habitability, be structurally self-standing, reduce flammability, and

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https://doi.org/10.1016/j.enbuild.2022.112035
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maintain cost [6]. The materials of the GFT include a high-density polyethylene (HDPE) outer layer, flexible aluminium poles supporting the dome form, a HDPE inner layer, and a light polycotton inner lining.

Considering the recent introduction of the GFT as a potential replacement for the SFT, this article aims to shed light on how differences in material and morphology affect tent thermal performance and to assess the extent to which the new GFT design achieves design objectives in relation to improved insulation against heat and cold.

Thermal performance of the SFT and other humanitarian shelters has been the subject of several studies. Pöschl [13] tested the SFT in both hot and cold climatic conditions, with experimental and simulation results supporting conclusions about effective practical design changes to improve thermal performance: namely, reduced fabric thermal transmittance (U-Value) and increased fabric reflectivity to deal with cold and hot conditions respectively. Manfield et al. [8] addressed both the material performance and the social context of tent use in cold climates, suggesting that technical innovations such as an additional insulation layer must be considered in the context of social behaviour of tent users and combined systematically with other measures - including clothing, bedding and active heating – in context-specific responses. Crawford et al. [4] assessed and compared thermal performance of two prototype shelters, leading to experimental design recommendations such as use of multiple evenly spaced sensors and placement of sensors near fabric surfaces. Cornaro et al. [3] measured thermal performance of a prototype tent that integrates photovoltaic cells, as a precursor to the development of a simulation model.

Other related studies employed experimental methods to measure thermal performance in support of the development of models that simulate this performance under different conditions. Obyn et al. [10] undertook experimental testing in three locations to collect data that enabled development of a simulation model, finding that modelling tent fabric with properties of glazing enables accurate reproduction of air permeability and transmittance characteristics of the SFT envelope. Fosas et al. [22] developed simulation models of six shelter designs used at the Azraq refugee camp in Jordan, highlighting the utility of building simulation methods to support evidence-based decision-making by organisations engaged in providing shelter assistance.

A third, group of studies use survey methods to assess thermal comfort of occupants of humanitarian tents. Albadra et al. [1] surveys occupants of rigid shelters in two refugee camps in Jordan, finding that comfort ranges identified by the Predictive Mean Vote (PMV) underestimate the wider range of temperatures at which refugee occupants felt comfortable. Susanti [23] found that standard measures of thermal comfort are inappropriate for humanitarian shelters, noting that surveyed occupants felt comfortable at temperatures outside the PMV range.

Considering the potential expansion in use of the GFT alongside continued use of the SFT, this article describes research undertaken with two objectives:

1. to measure and compare the thermal performance of the GFT, the SFT and the SFT with an additional shade net, specifically in relation to heat loss in cold conditions and heat gain in hot conditions, and
2. to develop simulation models for each tent to enable simulated comparison of tent performance in various climatic situations.

The article contributes to the discourse on thermal performance of humanitarian tents. Standard experimental methods have been used in accordance with comparable studies [4,10,11]. The novelty of this study lies in the application of these methods to a new test subject – the GFT – enabling the novel comparison of the thermal performance of the GFT with that of the SFT. The research also contributes to better understanding of the effects of tent material and morphology on thermal performance, within constraints circumscribed by a fabric envelope. In relation to the practice of humanitarian assistance, the article provides information to support decisions regarding tent selection. Section 2 describes research materials and methods. Section 3 presents results. Section 4 discusses these results. Section 5 concludes.

2. Materials and methods

Research involved two related components – *experimentation* in which data describing actual conditions inside and outside tents was recorded, and *simulation* in which models of tents were developed and calibrated using experimental data.

2.1. Tents

Experimental testing involved three variants of the two tents: 1) the GFT, 2) the SFT, and 3) the SFT with additional shade net (SFT+SN). The additional shade net is a standard item that is designed for use with the SFT to improve thermal performance (i.e., to reduce internal heat gain) in hot conditions. Inclusion of the SFT+SN as a third test subject enables assessment of the impact of this standard item upon SFT thermal performance. The geometry and materials of the tents are presented in Fig. 1. Table 1 summarises material characteristics and other characteristics relevant to the use of each tent in humanitarian response.

2.2. Experimentation

The three tent variants were erected at a test site at Fribourg, Switzerland, as presented in Figs. 2 and 3. The tents were kept in place for a period of seven months, which encompassed two test campaigns that measured two aspects of thermal performance:

1) Heat gain in hot climatic conditions, tested during a 7-day period from 10.07.2019 to 16.07.2019;
2) Heat loss in cold climatic conditions, tested during a 5-day period from 18.01.2020 to 22.01.2020.

From each test campaign, data from a single 24-hour period was required for comparison across the three tent subjects, hence the difference in duration of each campaign was not significant for test results.

During each campaign, a consistent array of sensors was installed in each tent to measure internal air temperature, surface temperature and relative humidity at different heights above floor level. The arrangement of sensors is presented in Figs. 4 and 5 (noting the consistent arrangement of sensors in the SFT and SFT+SN). Air temperature and relative humidity were measured by HOBO U12 thermocouples (Onset Computer Corporation) positioned centrally in each tent at: 0.10 m, 0.60 m, 1.10 m and 1.70 m above floor level. Surface temperature was measured by HOBO UX120 thermocouples attached to the internal surface of the polycotton inner lining of each tent at 0.50 m, 1.00 m, 1.50 m and 2.00 m above floor level. Data were recorded at five-minute intervals. Tent openings (doors and windows) were kept closed during the test periods. Concurrent air velocity measures were taken at the centre of each tent, though were excluded from further analysis considering low recorded values (averaged < 0.06 m/s).

In addition to these measurements, the air change rate of each tent was measured to understand differences in ventilation and air tightness. Air change rates were measured during the winter test

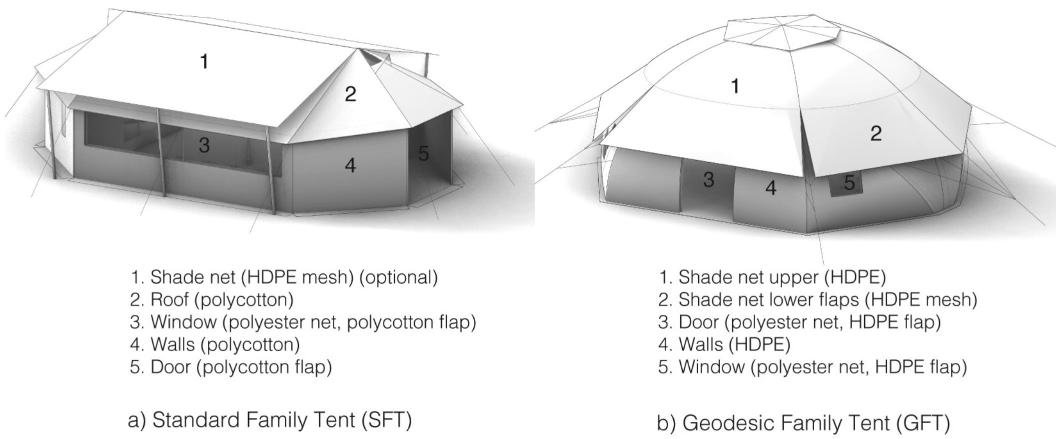

Fig. 1. SFT (shown with optional shade net) and GFT geometry and materials.

Table 1
Tent properties.

	SFT	SFT+SN	GFT
Internal area	16.0 m^2	*As per SFT*	21.5 m^2
Internal volume	~29 m^3	*As per SFT*	~37 m^3
Outer envelope material	Polycotton (60/40 – 350 g/m^2)	*As per SFT*	HDPE (165 g/m^2)
Inner envelope material	–	*As per SFT*	HDPE (165 g/m^2)
Inner lining material	Polycotton (60/40 – 130 g/m^2)	*As per SFT*	Polycotton (60/40 – 130 g/m^2)
Floor material	HDPE (woven)	*As per SFT*	HDPE (woven)
Structural material	Steel (painted)	*As per SFT*	Aluminium
Outer shade net material	–	HDPE mesh	HDPE mesh[a]
Packed weight	55 kg	60 kg	48 kg
Packed volume	~0.28 m^3 (2 packages)		~0.28 m^3 (1 package)
Price	CHF350	CHF530	CHF520

[a] The tested version of the GFT included woven mesh HDPE shade flaps. In later versions, shade flap material was changed to the same HDPE fabric used for the outer envelope.

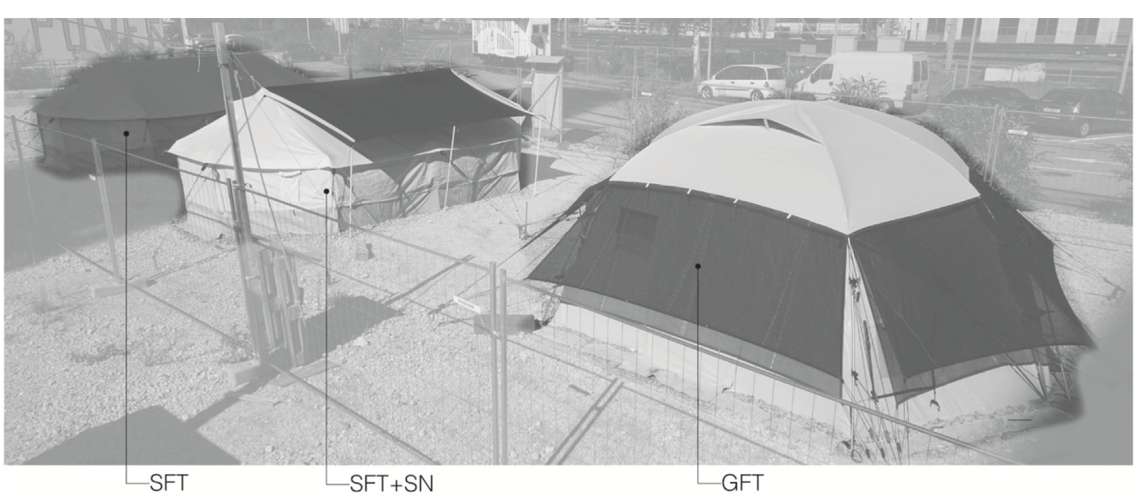

Fig. 2. Test site photograph.

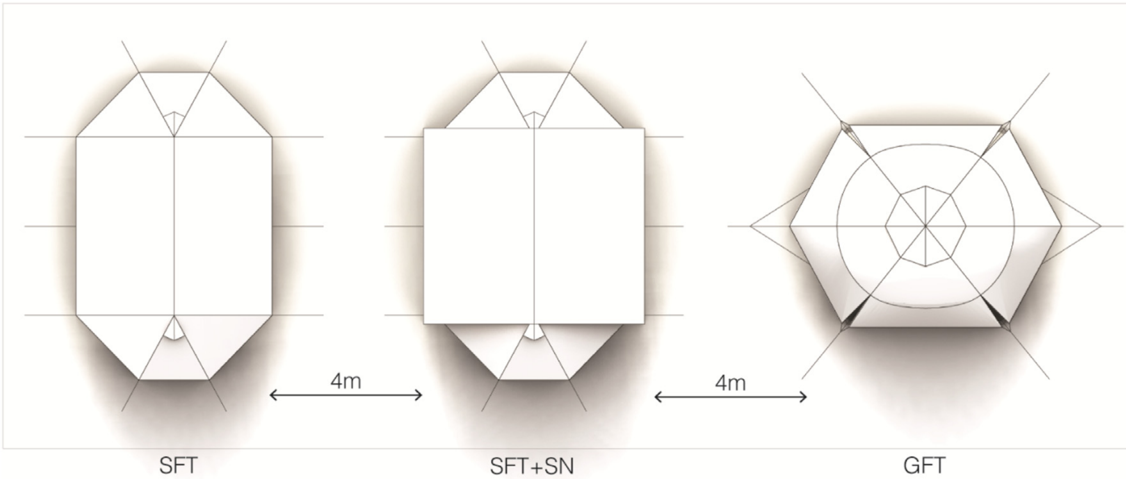

Fig. 3. Test site plan.

campaign using the CO2 decay method. CO2 was injected into each tent to a concentration of ~ 3000 ppm, then, decay of the CO2 level due to infiltration and natural ventilation was recorded by a CO2 sensor (HOBO MX1102, Onset Computer Corporation) over a one-hour period at one-minute intervals. During the decay period, the variation of CO2 concentration inside the tent could be described using the mass balance equation (1) and the real-time CO2 level could thus be interpreted as equation (2) by solving equation (1).

$$\frac{dC(t)}{dt} = -a * (C(t) - C_{out}) \quad (1)$$

$$C(t) = (C_0 - C_{out}) * e^{-at} + C_{out} \quad (2)$$

where, $C(t)$ is the indoor CO_2 concentration (ppm); C_{out} is the average ambient CO_2 level during measurement (ppm); C_0 is the CO_2 concentration at the beginning of the decay (ppm); t is the elapsed time after CO_2 injection (hour); a is the air change rate (per hour). Equation (2) can be then written as equation (3) using logarithmic conversion:

$$\ln(C(t) - C_{out}) = -a * t + \ln(C_0 - C_{out}) \quad (3)$$

Therefore, through linear fitting ln($C(t)$-C_{out}) versus t, we obtained the air change rate, which equals to the opposite number of the fitting slope.

Sensible heat load associated with tent occupants was simulated using incandescent light bulbs. In each tent, an array of 36 light bulbs with a total load of 450 W was placed at 0.10 m above floor level (see Fig. 4). The light arrays remained on throughout each test period. The output of 450 W simulated the heat load of a family of five occupants – one adult male, one adult female and three children – taking into account a 60 W/m^2 metabolic rate for seated, rested activity [2] and average body surface areas of 1.80 m^2 for adult males, 1.60 m^2 for adult females and 1.2 m^2 for children [8], with the simulated heat load of 450 W approximating the calculated average heat load of 420 W.

Local climatic conditions were recorded by weather stations located approximately 80 m from the test site. Climatic data collected included air temperature and relative humidity (HOBO U12-012, Onset Computer Corporation), wind speed and direction (SensoAnemo 5100LSF, SENSOR Electronic) and solar irradiance (HOBO RX2150, Onset Computer Corporation).

2.3. Simulation

A simulation model was developed for each tent variant. Models were first developed in DesignBuilder software [5]. Material attributes were assigned, and simulations performed with the EnergyPlus simulation engine [18]. The weather files, used in EPW format with hourly data, have been generated using Meteonorm software [11].

Models were calibrated using experimental data from both summer and winter test campaigns. The calibration process involved comparing simulation data with experimental data (from sensors) in a three-stage process. Firstly, an artificial climate file was created, using the actual outdoor temperature and humidity data measured during the two test periods, to serve as input for the energy model. Secondly, simulations were launched and compared with experimental air temperature results. Thirdly, from initial parameters adopted from Obyn et al. [10], the physical parameters of the models – primarily air permeability and radiant heat transmission - of the models were iteratively adjusted until model behaviour was assimilated to experimental results. Material characteristics of the calibrated simulation models are presented in Table 2.

3. Results

3.1. Summer experimental campaign

Data collected during the 7-day summer test campaign are summarised in Table 3 and presented in Annex 1. For comparison of the three tents under the same climatic conditions, a single representative 24-hour period – from 00:00 to 23:59 on 10.07.2019 – was selected as the focus of further examination. This 24-hour period was selected due to the minimized influence of cloud cover and other exogenous variables such as occasional opening of tent doors.

Mean air temperature (across heights above floor level) in each tent is plotted with outside air temperature and solar irradiance in Fig. 6, supporting several observations:

1) During daylight hours (05:33 – 21:21), the GFT and SFT+SN exhibited similar thermal performance, characterised by internal temperatures 1.4 – 9.4 °C above outside air temperature and maximum mean internal air temperature of 30.9 °C occurring at 16:05;

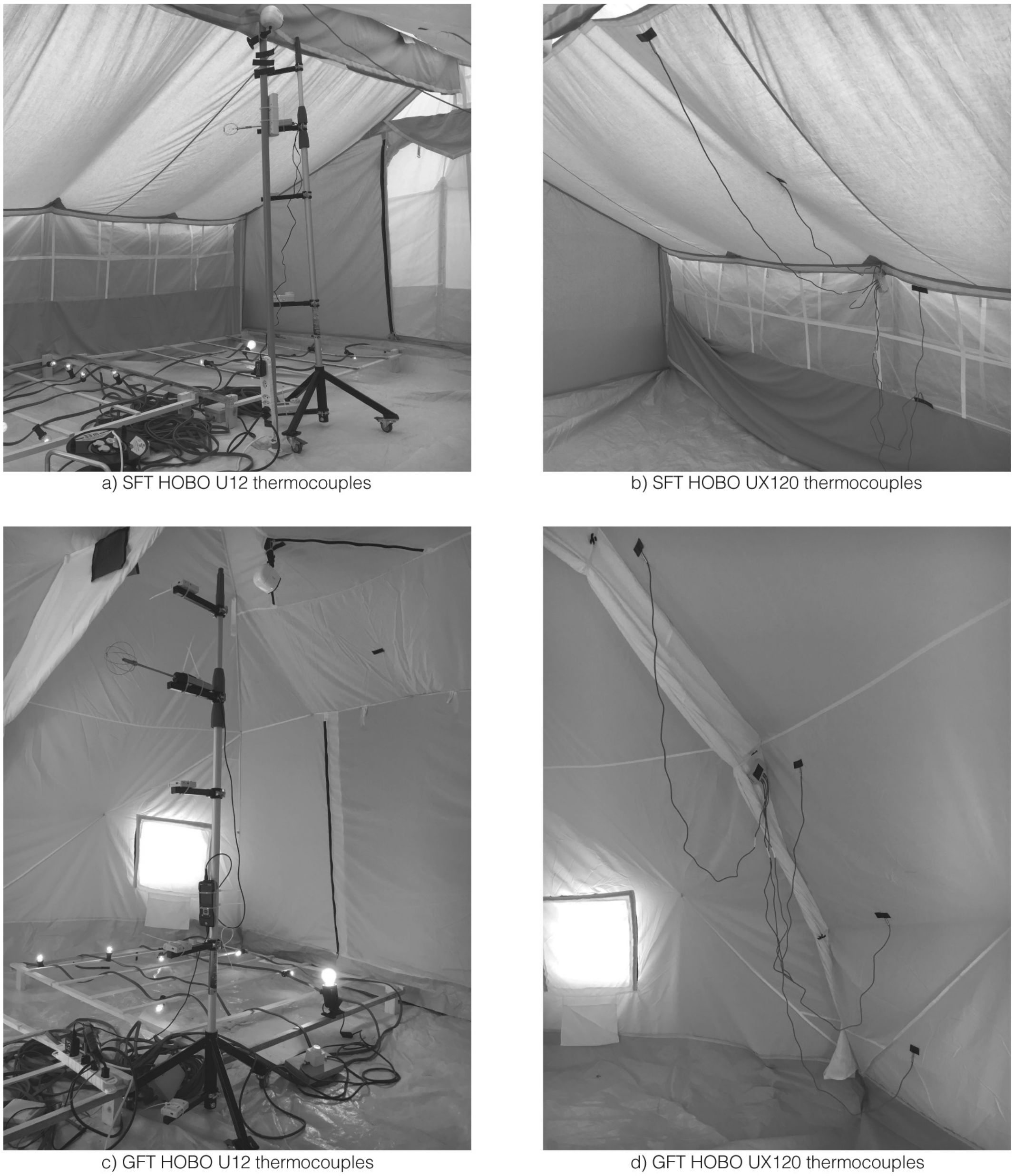

Fig. 5. Photographs of sensor layouts – SFT and GFT.

2) During daylight hours, thermal performance of the SFT was characterised by internal air temperatures 1.6 – 17.0 °C above outside air temperature and maximum mean internal temperature of 38.4 °C, occurring at around 14:50;
3) Outside daylight hours, the three tents exhibited similar thermal performance characterised by temperatures 1.4 – 5.1 °C above outside air temperatures and minimum temperatures of 18.2 – 19.5 °C occurring around 23:55;
4) A temporary drop in internal air temperature of the GFT by 3.7 °C (12%) at around 17:00 coincides with the shadow from an industrial chimney that temporarily reduced heat gain from direct solar irradiation. This temporary drop in air temperature of the GFT is also reflected in Figs. 7, 8 and 12 (c).

Mean surface temperature (across heights above floor level) in each tent is plotted with outside temperature and solar irradiance in Fig. 7, indicating that, for each tent, mean surface temperature follows a pattern similar to mean air temperature. In general, during daylight hours, surface temperature was around 1 °C hotter than air temperature, while, outside daylight hours, surface temperature is around 1 °C lower than air temperature.

Vertical stratification of air temperature in each tent is presented in Fig. 8, which plots differences between temperatures at 0.10 m and 1.70 m above floor level in each tent, supporting two observations:

1) During daylight hours, the three tents behave similarly in relation to heat stratification, with temperatures around 2–3 °C hotter at 1.70 m height,
2) Outside daylight hours, the three tents also behave similarly in relation to heat stratification, with no significant difference between temperature at the upper and lower levels.

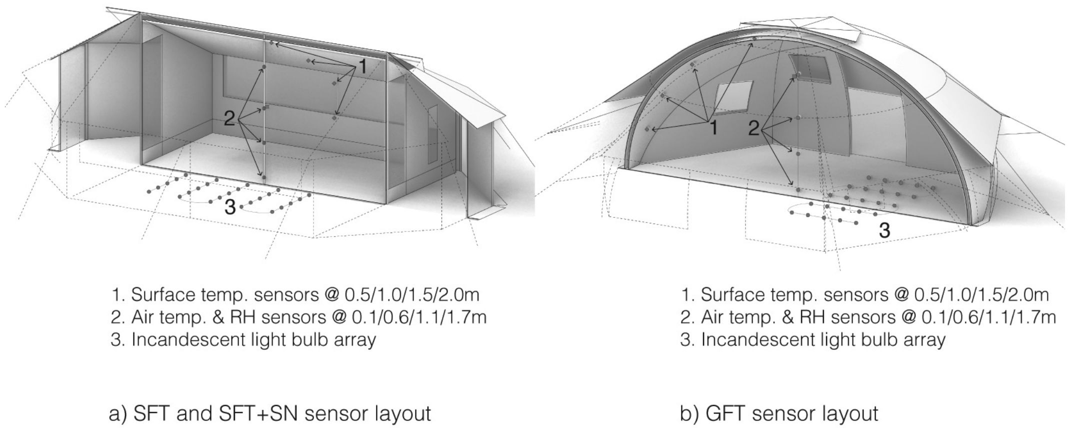

Fig. 4. Sensor layouts – SFT, SFT+SN and GFT.

Table 2
Simulation model envelope performance settings (developed from [10] and experimental data).

	SFT	SN (outer shade net)	GFT
Main composition	Polycotton	HDPE	HDPE
Thermal transmittance U-value ($W/m^2.K$):			
Walls	5.68	–	4.75
Roof	6.85	–	5.82
Floor	5.68	–	4.75
Solar heat transmittance (SHGC) (%)	20.44	0.5	41.8
Light transmittance (LT) (%)	16.48	0.09	0.05
Air tightness – closed (ACH)	2.08–2.32	–	1.43
Air tightness – open (ACH)	21.36–22.22	–	13.43

3.2. Winter experimental campaign

Data collected during the 5-day winter test campaign are summarised in Table 4 and presented in Annex 2. For comparison of the three tents under the same climatic conditions, a single 24-hour period – from 00:00 to 23:59 on 19.01.2020 – was selected as the focus of further examination. This 24-hour period was selected due to the minimized influence of exogenous variables such as occasional opening of tent doors and exceptionally high winds.

Mean air temperature (across heights above floor level) in each tent is plotted with outside air temperature and solar irradiance in Fig. 9, supporting several observations:

1) During daylight hours (08:06 – 17:11), thermal performance of the three tents was similar, except during a period around 11:50 – 14:15, when divergence peaked at around 13:30 with mean internal temperatures of 10.9 °C in the SFT, 8.8 °C in the SFT+SN, and 8.3 °C in the GFT;
2) Outside daylight hours, the GFT and SFT+SN exhibited similar thermal performance, characterised by internal mean air temperatures consistently around 3.9 °C higher than outside air temperature;
3) Outside daylight hours, thermal performance of the SFT is characterised by internal mean air temperatures consistently around 2.4 °C higher than outside air temperature.

Mean surface temperature (across heights above floor level) in each tent is plotted with outside air temperature and solar irradiance in Fig. 10, which supporting several observations:

1) During daylight hours, mean surface temperature for each tent followed a similar pattern to mean air temperature, with close correspondence between tents diverging at around the period of 11:30 – 13:30;
2) During daylight hours, mean surface temperature of each tent was consistently around 1 °C higher that mean surface temperature;
3) Outside daylight hours, the GFT and SFT+SN exhibited similar thermal performance, characterised by internal surface temperatures consistently around 2.0 °C higher than outside air temperature;
4) Outside daylight hours, thermal performance of the SFT is characterised by internal mean surface temperatures generally around 1.0 °C higher than outside air temperature;
5) Outside daylight hours, for each tent mean internal surface temperatures were generally around 2.0 °C lower than mean internal air temperature;

Stratification of air temperature in each tent is presented in Fig. 11, which plots differences between the temperatures at 1.70 m and 0.10 m in each tent, supporting several observations:

Table 3
Descriptive data* of dry-bulb air temperature, surface temperature and relative humidity recorded during the summer test period (averages of four measurement heights).

	Air temp (°C)			Surface temp (°C)			Relative humidity (%)		
	ave ± sd	P5	P95	ave ± sd	P5	P95	ave ± sd	P5	P95
GFT	23.3 ± 4.6	17.5	31.3	22.7 ± 5.6	15.8	32.6	59 ± 4	35	78
SFT + SN	23.1 ± 5.4	16.4	32.4	22.7 ± 6.1	15.2	33.4	54 ± 17	27	80
SFT	24.5 ± 7.7	15.7	38.5	23.9 ± 8.5	14.2	39.7	51 ± 20	20	79

*P5 = 5th percentile, P95 = 95th percentile.

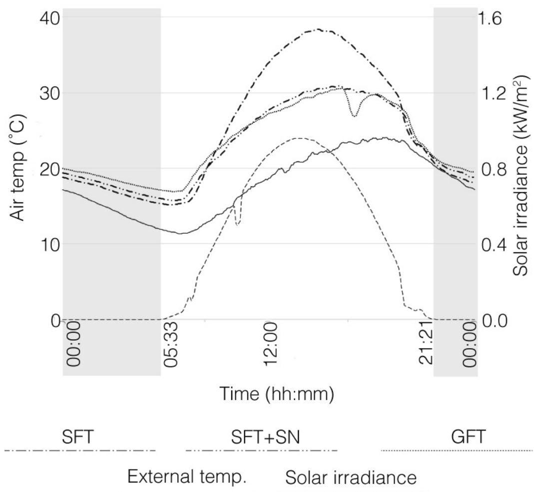

Fig. 6. Air temperature (mean), all tents, 10.07.2019.

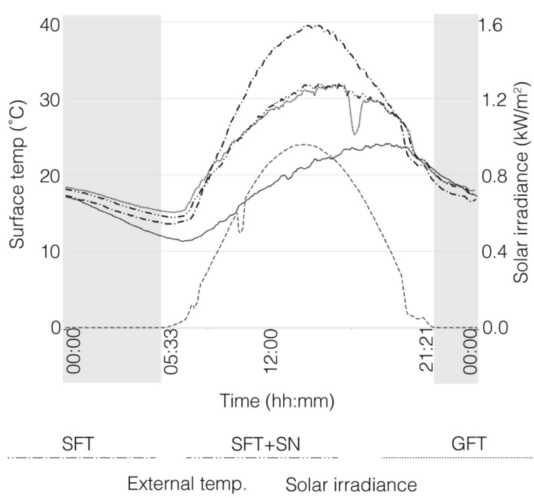

Fig. 7. Surface temperature (mean), all tents, 10.07.2019.

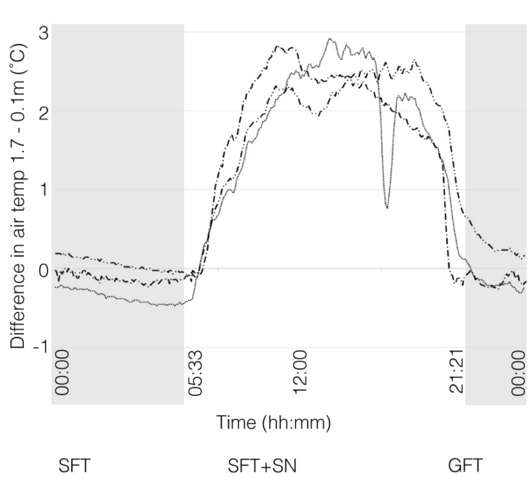

Fig. 8. Air temperature stratification, all tents, 10.07.2019.

1) During daylight hours, increasing differences between temperatures at upper and lower levels peaked around 12:00 with differences of around 2.0 °C in the SFT+SN, 1.5 °C in the GFT, and 1.0 °C in the SFT;
2) Outside daylight hours, the SFT and SFT+SN performed similarly in relation to temperature stratification, with no significant difference between temperatures at upper and lower levels;
3) Outside daylight hours, in the GFT, temperatures at lower levels were generally around 0.40 °C higher than air temperature at higher levels.

3.3. Air tightness and ventilation

Air change rates measured for each of the three tents during the winter test campaign are presented in Table 5. For each tent, two air change rates are presented – *closed* for which all doors and windows were closed, and *open* for which all doors and windows were opened. Thus, closed air change rates relate to the potential in cold conditions to reduce heat loss arising from air leakage through air-permeable materials and material assemblies, while open air change rates refer to the potential to reduce heat gain in hot conditions through ventilation. Results for the closed condition indicate higher air change rates in the SFT, suggesting greater heat loss due to air leakage in cold conditions compared to the GFT. Results for the open condition also indicate higher air change rates in the SFT, suggesting improved ventilation in hot conditions. Thus, opening windows of the SFT has a far greater impact on ventilation compared to opening windows of the GFT, reflected in the increase by around 20 air changes per hour in the SFT compared to an increase of around 12 air changes per hour in the GFT, suggesting improved ventilation in hot conditions.

3.4. Simulation models

The accuracy of simulation models is reflected in the degree of correspondence between measured and simulated internal air temperatures. Simulated and measured internal and external air temperature is plotted in Fig. 12 for 10.07.2019 (i.e. the summer test period), and in Fig. 13 for 19.01.2020 (i.e. the winter test period).

The differences observed between measured and simulated temperatures – which are most prominent for SFT and SFT+SN – are mainly due to the difficulties adjusting the building energy model to simulate the uncontrolled infiltrations between indoor and outdoor air. As soon as the indoor temperature exceeds a certain value, the model increases the exchange by simulating the opening of the plastic layer covering the perforated ventilation grid. This was modelled as windows assuming a hypothesis of 20% of opening area referring to the fabric density of this perforated element. To improve the current model, CFD studies could determine air inflow through the perforated fabric and the airtightness of each tent. This phenomenon seems more accentuated due to the geometry of the SFT and SFT+SN compared to the GFT.

Utility of the simulation models includes the potential to compare pre-emptively the performance of the different tents in specific locations, with this pre-emptive comparison enabling better informed decisions about which tents to supply in particular humanitarian situations. In Fig. 14, the internal air temperature of each tent is simulated for Lesbos, Greece on 15.08.2020, when a new camp for refugees, which included around 260 GFTs and 680 SFTs, was under construction following a fire at the original camp. Fig. 14 (a) presents simulations with all tent openings (doors and windows) closed, while Fig. 14 (b) presents simulations with all openings opened.

Table 4
Descriptive data* of dry-bulb air temperature, surface temperature and relative humidity recorded during the winter test period (averages of four measurement heights).

	Air temp (°C)			Surface temp (°C)			Relative humidity (%)		
	ave ± sd	P5	P95	ave ± sd	P5	P95	ave ± sd	P5	P95
GFT	3.2 ± 2.9	−0.1	9.2	2.5 ± 4.1	−1.5	11.4	72 ± 7	55	80
SFT + SN	3.2 ± 3.2	−0.5	10.0	2.8 ± 4.4	−1.6	13.1	69 ± 9	50	79
SFT	2.8 ± 3.6	−1.3	10.3	2.0 ± 5.0	−3.0	13.7	68 ± 10	47	80

*P5 = 5th percentile, P95 = 95th percentile.

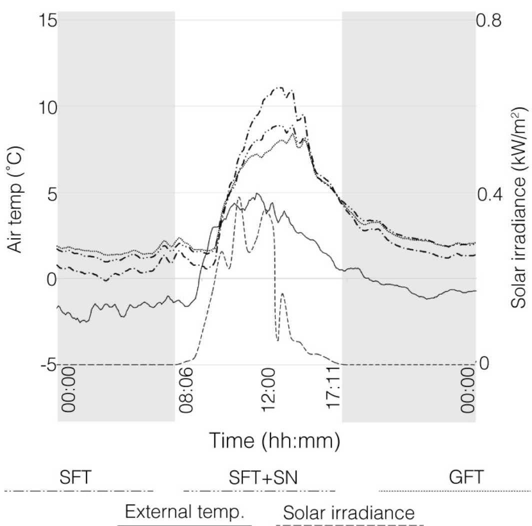

Fig. 9. Air temperature (mean), all tents, 19.01.2020.

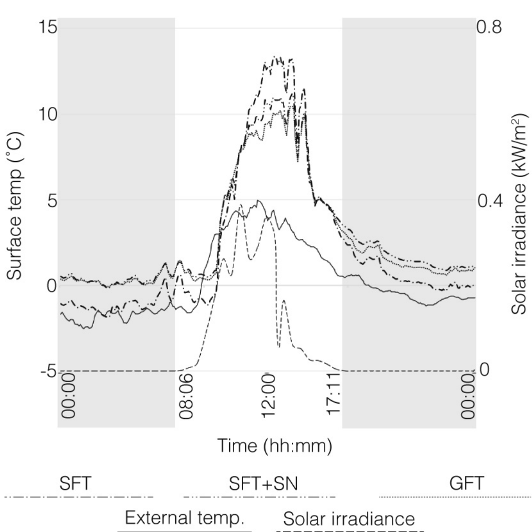

Fig. 10. Surface temperature (mean), all tents, 19.01.2020.

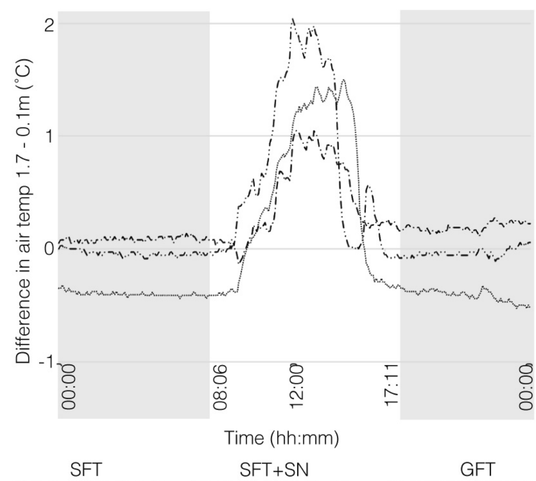

Fig. 11. Air temperature stratification, all tents, 19.01.2020.

4. Discussion

In general, the GFT and SFT+SN exhibited similar patterns of thermal performance that differed from the performance of the SFT.

Table 5
Measured air change rates.

	Air changes per hour (ACH,1/h) Closed	Open
SFT	2.083	22.22
SFT+SN	2.326	21.36
GFT	1.435	13.43

The SFT exhibited greater radiant heat gain during daylight. The addition of shade layers to the GFT and SFT+SN reduced internal temperature in these tents by up to 30% compared to internal temperatures in the SFT. The similarity in performance of the GFT (HDPE envelope material) and the SFT+SN (polycotton envelope material) highlights that a shade layer (in addition to the envelope layer) has significantly greater effect upon radiant heat gain than the change in tent form and envelope material. Considering later versions of the GFT included *woven HDPE* on shade flaps – as opposed to the *HDPE mesh* shade flaps of the tested version – further testing could clarify the impact of shade net material upon radiant heat gain. Further testing could also clarify whether addition of a further shade layer – i.e., two shade layers – could support further reduction in radiant heat gain.

The additional shade layer of the GFT and SFT+SN also affected heat loss in the night during the summer test period and in the day and night during the winter test period. Internal temperatures of the GFT and SFT+SN were up to 2 °C higher at night than internal temperature in the SFT. This difference suggests that the outer shade layers - although only partially covering the tent envelope and separated from the envelope by a gap of up to around 15 cm – reduces heat loss by reflecting heat radiation from inside the tent. This 2 °C difference is relatively small though potentially significant considering the effect it could have on occupant comfort (and heating stove fuel consumption) associated with occupation

[2] Prices noted here are the prices of purchase from the supplier Alpinter SA in February 2019. Tents and shade net were purchased in Swiss Francs (CHF). Prices have been converted to US dollars (USD) for wider comparability using the exchange rate at the time of purchase.

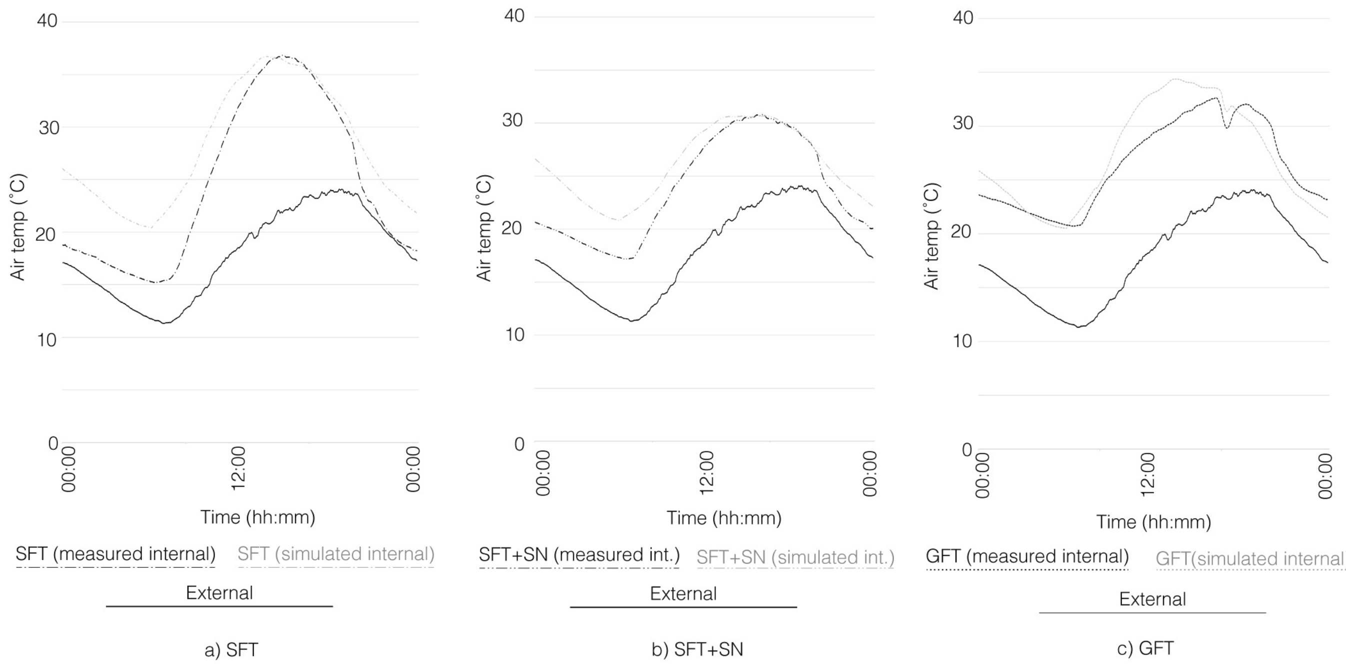

Fig. 12. Simulated and measured air temperature at Fribourg, Switzerland on 10.07.2019.

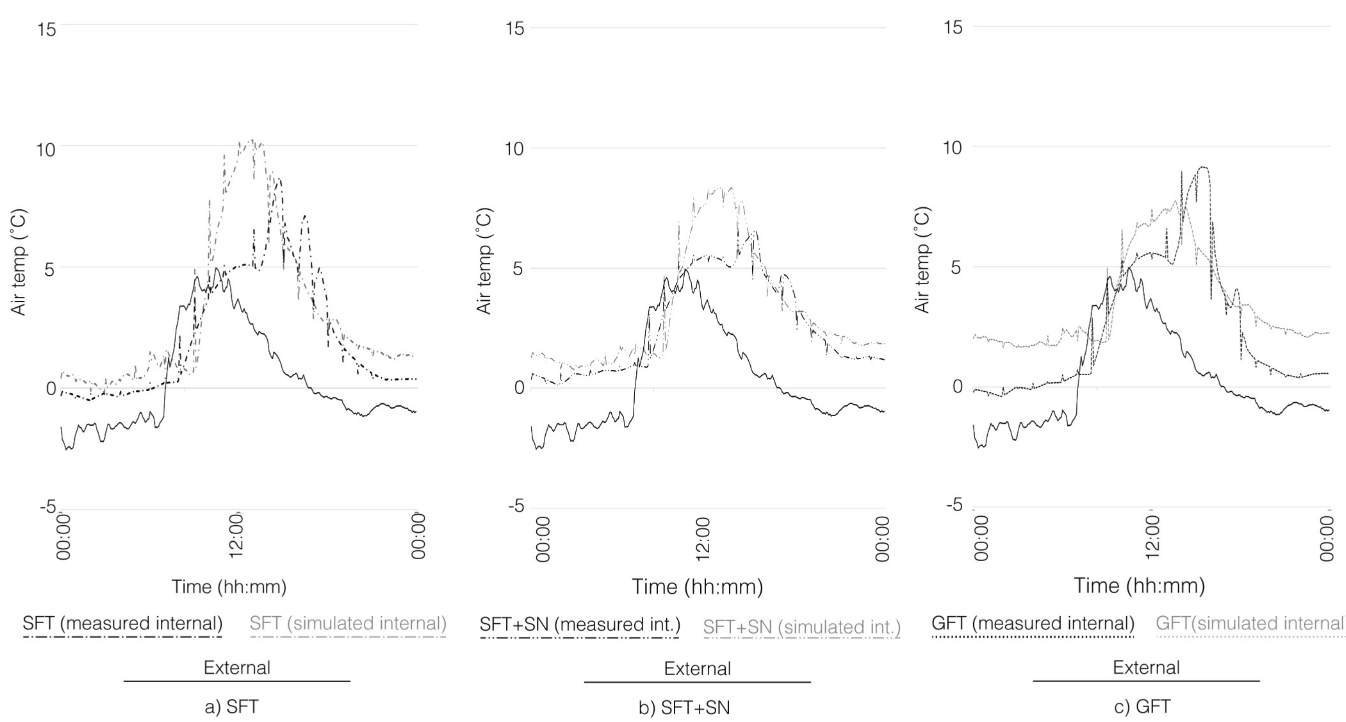

Fig. 13. Simulated and measured air temperature at Fribourg, Switzerland on 19.01.2020.

of the tents in cold conditions. Further testing could clarify whether changes in shade net design and material can optimise this insulation effect.

Improved thermal performance of the GFT in cold conditions may be partially attributed to air tightness. When all windows are closed – a normal scenario in cold conditions – the air change rate of the GFT was more than 30% lower than that of the SFT, suggesting greater air tightness and therefore lesser heat loss. While improving thermal performance, the increased air tightness also has implications for ventilation and health when use of wood heating stoves in tents affects indoor air quality, requiring adequate ventilation to maintain healthy living conditions [4].

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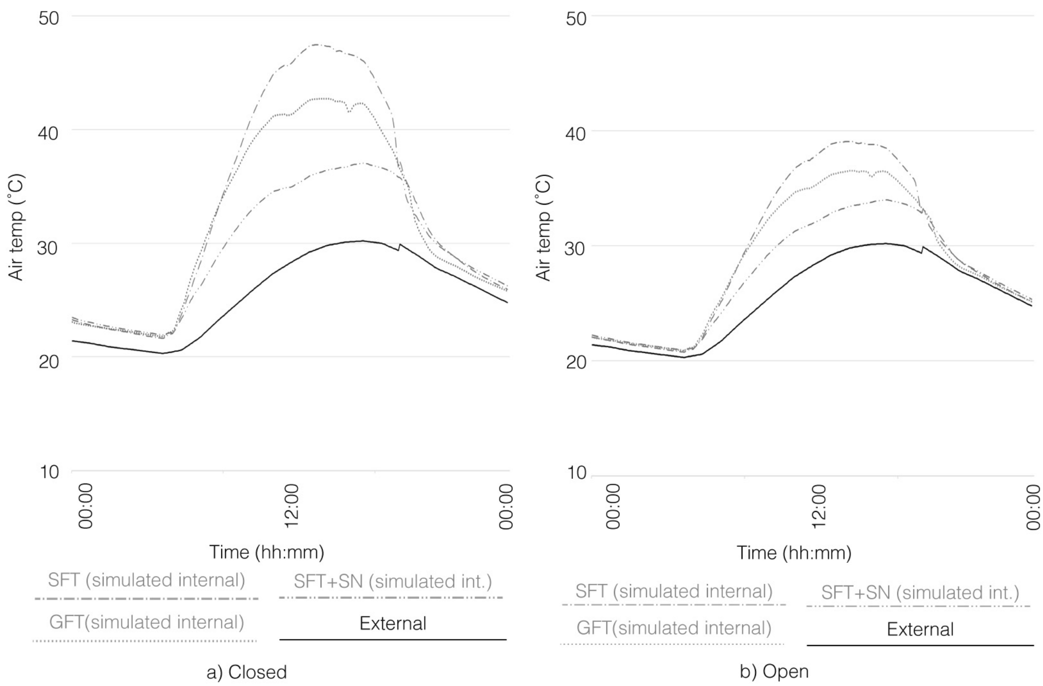

Fig. 14. Measured outdoor and simulated indoor temperature at Lesbos, Greece on 15.08.2020.

Reduced radiant heat gain, reduced conductive heat loss and increased air tightness of the GFT compared to the SFT suggest a degree of success in achieving the stated aim of providing "better insulation against heat and cold" [6]. However, similar thermal performance improvements were achieved by the use of a shade net with the SFT. Assuming continued use of the SFT, the shade net should be included as a standard component in SFT specifications. Notwithstanding cost implications (the price of the shade net was around USD 200, compared to around USD 380 for the SFT), standard packaging and warehousing of shade nets with the SFT would support widespread improvements in thermal comfort in the context of prepositioning and rapid procurement of emergency supplies. Notably, the total price of the SFT+SN (around USD 580) was slightly higher than that of the GFT (around USD 570).[2]

Increased air tightness of the GFT, reflected in lower air change rates compared to the SFT, also suggests a degree of success in reducing heat loss through air leakage when all tent openings are kept closed in cold conditions. Conversely, greater air tightness of the GFT when all tent openings are kept open for cross-ventilation indicates a lower capacity for ventilation to reduce heat gain in hot conditions. Notably, while increasing air tightness reduces heat loss through air leakage, it also reduces ventilation and internal air quality. This effect of air tightness upon ventilation is particularly important in situations where combustion stoves (e.g., wood stoves) are used for heating inside tents.

Notwithstanding improved thermal performance of the GFT and SFT+SN, none of the tents provided comfortable internal conditions during summer nor winter test campaigns. During the summer campaign, when the outside temperature did not exceed 25 °C, temperature inside the three tents exceeded 30 °C during the hottest period of the day. Despite potential for ventilation by opening doors and windows, and the increased adaptability of tent occupants [1], uncomfortably hot temperatures inside tents in hot climatic conditions are expected to restrict occupation during hotter periods of the day. In winter campaign, when outside temperature at night dropped to −2°C, temperatures inside the tents was in the range of 0–2 °C. Thus, in colder conditions, additional insulation via clothing or bedding and heating via stoves would be required.

Beyond thermal performance, other characteristics distinguished the design and performance of the GFT from that of the SFT during the 7-month test period. While the SFT and GFT have similar internal floor areas, the dome form of the GFT provides steeper walls that enable better access to peripheral areas of the floor plan, thus providing greater usable internal area and volume. Moreover, the GFT was more structurally stable during the test period compared to the SFT and SFT+SN; during the 7-month period, the SFT and SFT+SN required regular maintenance (e.g., tightening guy ropes) and both the SFT and SFT+SN partially collapsed on one occasion, while the GFT required no significant maintenance or adjustments.

Notwithstanding these performance improvements of the GFT, actual impact on living conditions in emergency situations depends upon dissemination of this new design. The case of the Ikea Shelter – a well-publicised innovation that failed to have a significant impact on shelter assistance [12] - demonstrates that improved performance does not assure dissemination and impact. However, the simple tent form of the GFT, like that of the SFT, is compatible with existing institutional arrangements for humanitarian shelter, including arrangements for procurement and logistics. Thus, the GFT entails an incremental innovation of tent design that has strong potential for practical impact upon shelter assistance.

In this context, several directions for further incremental improvements in the GFT design were highlighted during this research. Improvements in insulation against radiant heat gain through increased reflectivity of shade-layer materials and/or through addition of a further shade layer(s) warrant investigation. Improvements in insulation against conductive heat loss through addition of an internal insulation layer utilising for support the improved structural stability of the GFT also warrant further investigation. Improvements in air tightness and ventilation of the GFT could be achieved through changes in closing mechanisms of doors

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and windows. Improved security could be provided by incorporation of a rigid, lockable door within the GFT (perhaps as an add-on feature). In isolation, these design changes may provide marginal improvements in tent performance, which, in combination, could have significant impacts upon humanitarian shelter assistance.

Limitations of the study stem from differences between experimental conditions and actual conditions of tent use, which impact on both the measurement of thermal performance as well as the measurement and experience of thermal comfort. Steps were taken to simulate some aspects of tent occupation, such as simulation of a heat load. However, actual occupation of tents includes variations in heat loading, vapour loading, air infiltration from opening and closing of doors and windows, and other occurrences that affect thermal performance but were not simulated. Moreover, experimentation measured surface and air temperatures inside tents; however, these temperatures do not correlate exactly with thermal comfort, which depends on other factors including occupants' personal tolerances.

5. Conclusions

Improvements in the performance of humanitarian tents can positively impact the large numbers of people displaced by conflict and disaster and in need of emergency shelter. The Geodesic Family Tent (GFT) is an innovation in emergency shelter that was released in 2018 to provide, among other objectives, better thermal performance and internal comfort compared to the stalwart of humanitarian shelter - the Standard Family Tent (SFT). This study intended to compare the thermal performance of the GFT and SFT and, in doing so, improve understanding about effects of tent material and morphology on thermal performance,

Four conclusions are drawn. First, the GFT and SFT+SN exhibited better thermal performance - i.e., lower radiant heat gain in hot conditions and lower conductive heat loss in cold conditions – compared to the SFT. During the hottest times of the day during the summer test campaign, temperatures in the GFT and SFT+SN were up to 10 °C lower than inside the SFT. During the coldest periods of the winter test campaign, temperatures in the GFT and SFT+SN were up to 2 °C higher compared to the SFT. Secondly, in spite of this improved thermal performance, none of the tents provided adequate insulation against heat gain and loss to ensure comfortable internal conditions in the summer and winter test conditions. In hotter conditions, radiant heat gain would limit comfortable occupation of each tent, while, in winter, conductive heat loss would require additional personal insulation (i.e. clothing and bedding) and/or space heating (e.g. a wood stove). Thirdly, the similar thermal performances of the GFT and SFT+SN highlight the greater significance of the addition of a shade layer in reducing radiant heat gain *and* heat loss compared to the effects of tent material and form on thermal performance. Fourthly, the GFT provides improved functionality - specifically in the increased usable internal volume and increased structural stability – which could improve the quality of emergency accommodation compared to the SFT.

Several directions for further research were identified. Further experimentation incorporating controlled variations in tent design - e.g., changes in the reflectivity of sunshade material – would improve understanding about specific effects of materials and morphology upon thermal performance. Improved measurement of air infiltration and leakage – including through measurement of air velocities at different locations within tents – could improve understanding about effects of tent morphology and fabrication upon this important aspect of thermal performance. Moreover, improved understanding of air infiltration and leakage could inform improvements in simulation modelling.

Finally, this study has investigated thermal performance of standard humanitarian tents - not occupant thermal comfort, which is a direction for further research. Considering the limited relevance of the PMV approach to thermal comfort modelling in relation to humanitarian tents [1,20], adaptive thermal comfort modelling may be more suitable for predicting occupant thermal comfort. Future research could also consider in-situ surveys of occupant subjective responses to thermal environments in humanitarian tents, which can form a basis for developing improved thermal performance modelling of tents and comfort management of occupants.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by grants from the Smart Living Lab, Fribourg, which included funding from Blue Factory Fribourg SA. We are grateful for the work of Claude-Alain Jacot in setting up the tent test site and the work of Kyra Michel and Anne Steullet in producing digital models of the tents.

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