Energy performance of temporary shelters

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Abstract. This paper analyzes methods for calculating energy consumption of temporary shelters for the purpose of reducing energy consumption for heating and improving the level of comfort. Mobile shelters are widely used by rescue emergency teams. Often such type of buildings has a limited access to reliable source of energy supply. Thus it is vitally important to make correct heat losses analysis to select proper capacity of energy source. The paper presents analysis of heat losses of rubber/fabric shelters without extra thermal insulation.

1. Introduction

Mobile temporary shelters are widely used for camps and rescue operations. Usually such shelters are placed in remote areas without connection to electrical grid or district thermal energy network. Mobile energy sources, mainly diesel engine with an electric generator are used for energy supply. Such solution has limited amount of energy which can be produced onsite with out extra supply. Thus, is a vitally important to make precis calculation of heating and cooling loads in order to ensure long term energy supply for mobile temporary shelters. Especially this is very important for rescue operation where optimal thermal comfort should be insured for victim care. In should be noted that not only thermal comfort is important, the human is health affected by CO and CO₂ concentration [1] in shelters. The main reason is insufficient ventilation due to limited energy source. Nowadays existing mobile energy solution can be supplied with extra storage [2]. The capacity of such units is limited in comparison to traditional energy sources [3]. Thus, thermodynamic properties of shelters’ envelope constantly improves [4] [5] which give possibility to improve overall energy performance and insure better thermal comfort and indoor air quality. Currently there is a lack of publicly available energy consumption calculation tools for extremely light temporary structures. Study [6] use ANSYS Fluent for natural convection inside the air gap for less energy consumption. However it should be mentioned that not all well know approaches on passive cooling [7] can be efficiently used in temporary shelter. ANSYS Fluent is pretty complicated software which is not commonly used by engineers. Tre IDA-ICE tool can be used for more simplified energy consumption calculations in tents [8]. In scope of this study the analysis of methods for calculating heat losses from temporary shelters was performed. Our purpose is to reduce energy consumption for heating and improve the level of comfort. Key ideas for calculating heat losses from shelters were comes from the Technical Report Natick/TR-79/017 [9]. In essence, these methods do not differ from the methods used for calculating heat losses for buildings and based on laws of thermodynamics [10] [11]. These methods slightly modified and extended in order to use for new materials and adopt results for dynamic energy simulations. The basis of all calculation methods is an irreversible process: heat transfer which may consist of three separate types of disseminating thermal energy (conduction, convection and radiation)
in various combinations. The structure of the paper is the following: first, we are going to look at methods for determining heat losses from shelters and provide a concrete example of calculation. Finally, we are going to compare the data with the values that were obtained using measuring instruments [12] and we will adjust some coefficients.

2. Materials and methods
There are two key types of heat loss from shelters: heat transmission through external structures (walls, ceiling, floor), and infiltration or air drainage toward the outside and influx of cold air inside. Strictly speaking, there is also the third type of heat loss - heat reflection from shelter surfaces but considering the relatively low surface temperature, its intensity is low (in accordance with the Stefan–Boltzmann law). Certainly, heat reflection should not be completely disregarded, however we are going to assume that heat reflection intensity is included in heat flux density from the shelter surface to the surrounding environment characterized by the heat transfer coefficient. Total heat loss can be calculated as sum of loss through heat transmission (including the radiation component) and heat loss through infiltration. Since our goal is to determine heat loss characteristics that do not depend of weather conditions at a certain moment, we are going to divide all expressions by \( \Delta T \) and thus acquire heat losses per one degree.

\[
L = \frac{\sum_{n} (Q_{c})_{n} + Q_{a}}{\Delta T} = \sum_{n} (U_{n} \Delta)_{n} + \rho c V_{a}
\]

where \( n \) is the number of shelter surfaces that should be addressed separately.

Heat losses from shelters are influenced by temperature as well as other weather conditions such as wind and clouds. Therefore, we are going to analyze the weather conditions that result in maximum heat losses, and weather conditions that result in minimum heat losses. Subsequently, we are going to compare the calculated data with the values that were obtained using measuring instruments. It could be assumed that maximum heat losses take place during nighttime with clear sky and moderate wind weather conditions. It can be assumed that shelter surface temperature in such conditions in equal to external air temperature. Infiltration takes place through doors that have not been closed tightly as well as through shelter material.

We are going to assume that minimum heat losses take place at cloudy sky with no wind weather conditions. Windless conditions mean that infiltration will be insignificant and heat transfer coefficients between the surface and external and internal air will be identical, i.e. \( U_{o}=U_{i} \). Shelter floor should be analyzed separately. In our example, shelter floor is ground, therefore it is necessary to evaluate ground temperature and apply the necessary heat transfer coefficient. Ground temperature in the winter can be assumed as 0\(^{\circ}\)C. It is important to understand that, additionally to the floor, a shelter has quite a high vertical temperature gradient and therefore temperature in the bottom part of the shelter must be used for calculating heat losses through ground. Additionally, we are going to assume that heat losses through ground practically coincide at both maximum and minimum heat losses.

3. Thermodynamic properties of shelters’ external envelope
Shelters are collapsible temporary structures that can be assembled quickly. Shelters serve as a refuge from adverse weather conditions, temporarily accommodating and housing human occupants, performing works, household needs as well as storing various materials in field conditions. In terms of structure shelters can be categorized as follows framed; Non-framed; Inflatable. Inflatable shelters require a very short assembly time. Framed shelters structures easily bear snow loads of up to 15-20 kg/m\(^{2}\) and wind loads of up to 30 m/sec.

Shelters can also be systematized according to their form, volume, material and number of layers. See Figure 1 for various forms of shelters. Wind resistance of shelters depends not only on the shelter material and the number of layers, but also on their shape.
Thermal conductivity and water resistance of shelters depend on the shelters’ material and number of layers. One-layer and two-layer enclosing fabric is commonly used. Multi-layer fabric is also used in shelters intended for use in winter. However, one must take into account that the assembly time of such shelters is longer, and they are typically used for long-term stationing. Thermal resistance of a modern non-insulated one-layer shelter is 0.33 m²K/W [13]. Correspondingly, the heat transfer coefficient is - 2.98 W/m²K. According to source data, thermal resistance of such shelters is 0.124 m²K/W. Thermal resistance of two-layer shelters is 0.60 m²K/W. Respectively, the heat transfer coefficient is -1.68 W/m²K [11]. For example, thermal resistance of standard TEMPER insulated fabric is 0.564 m²K/W [12]. According to the data of another source [13], thermal resistance of one-layer shelter fabric is 0.21 m²K/W. It is possible to increase thermal resistance to 0.39 m²K/W by means of using an additional layer of fabric and creating a fixed air layer. In order to improve a shelter’s thermo-mechanical properties, it is possible to use multi-layer fabric with vacuum heat insulation.

The use of aerogel enables to substantially decrease heat losses during winter, and limit heat influx during summer. In such a case, thermal resistance is 1.814 m²K/W. An additional option is to use spray polyurethane foam insulation. Polyurethane foam is sprayed on the shelter’s external surfaces, and it increases the existing structure’s thermal resistance to 1.25 m²K/W as it solidifies. Using foam is significantly cheaper than using aerogel fabric. However, it is no longer possible to relocate a shelter after applying polyurethane foam insulation, and thermal insulation works must be carried out by means of engaging an outsourced service provider. Also extra thermal insulation material should be carefully chose, taking into account exploitation conditions. Extra water leakage can significantly reduce thermal conductivity [14]. Also application of light weight metal structure can be considered as reliable solution [15] for fast camp assembly.

4. Evaluation of heat losses

Let us analyze an average general-purpose shelter (Figure 2).

Shelter floor is the ground, ground area is \( A_g = 50 \text{ m}^2 \), wall area is \( A_w = 60 \text{ m}^2 \), roof area is \( A_r = 2 \times 4.5 + 2 \times 22.1 = 53.2 \text{ m}^2 \). The proportion of heat transfer coefficient of the shelter material to shelter material thickness [10] is \( \frac{\lambda_e}{l} = 38 \frac{W}{\text{m}^2 \text{K}} \).

Let us assume that the difference between average indoor temperature and average outdoor temperature is \( \Delta T = 22.8^\circ\text{C} \). In turn, the difference between average indoor temperature and the
temperature in the shelter’s bottom part is \( \Delta T_g = 5.5^\circ C \). Heat transfer coefficient between indoor air and ground surface in this case [12] is \( U_g = 11.4 \text{ W/m}^2\text{K} \). Thus, heat losses through the ground at both maximum and minimum heat losses are \( L_g = \frac{U_g A_g \Delta T_g}{\Delta T} = \frac{11.4 \times 50 \times 8.5}{22.9} = 137.5 \text{ W/K} \). Heat transfer coefficients between the shelter surface and internal and external air in windless weather conditions equal \( U_o = U_i = 8.5 \text{ W/m}^2\text{K} \). Thus, heat losses from walls and roof are \( L_w, r = U_t (A_w + A_r) = 3.8 \times (60 + 53.2) = 430.2 \text{ W/K} \). Since infiltration at minimum heat losses may be disregarded, the result is: \( L_{\min} = 135.5 + 430.2 = 567.7 \text{ W/K} \).

In the maximum heat losses case, we must consider infiltration. \( L_A = \frac{Q_A}{\Delta T} = \rho c V_o \), where \( \rho c = 1.2 \frac{\text{kg}}{\text{m}^3} \times 1004.2 \text{ kg/m}^3 \cdot \text{K} = 1205 \frac{\text{W}}{\text{m}^2\text{K}} \). Let us assume that the shelter’s maximum air permeability is \( 0.0005 \text{ m}^3/\text{s} \cdot \text{m}^2 \), shelter surface area is \( 113.2 \text{ m}^2 \) but in this case we are going to consider only half of the surface area. Further, we are going to assume that air discharge through gaps between shelter walls and ground is \( 0.0045 \text{ m}^2/\text{s} \) shelter perimeter is \( 30 \text{ m} \). Therefore \( V_o = (0.0005 \times 113.3)/2 + 0.0045 \times 30 = 0.163 \text{ m}^3/\text{s} \). Thus, \( L_A = \rho c V_o = 1205 \times 0.163 = 196.4 \text{ W/K} \). At maximum heat losses \( U_t = 0 \) and \( U_g = 8.5 \), heat losses from walls and roof are \( L_w, r = U_t (A_w + A_r) = 6.9 \times (60 + 53.2) = 781.1 \text{ W/K} \). Thus, we acquire maximum heat losses \( L_{\max} = L_g + L_A + L_w, r = 137.5 + 196.4 + 781.1 = 1115 \text{ W/K} \).

As we can see, the difference between the minimum heat losses \( L_{\min} = 567.7 \text{ W/K} \) and the maximum heat losses \( L_{\max} = 1115 \text{ W/K} \) is significant. So, the weather impact on heat losses is very important.

5. Brief analysis and adjustment of obtained results

Let us analyze the functional connection of heat losses through ground \( L_g \) from the difference between the average indoor temperature and temperature in the bottom part of the shelter, i.e. let us analyze the function \( L_g (\Delta T_g) \), where \( \Delta T_g \) will be considered as the variable. Evidently, the functional connection is linear (Figure 4 right).

![The graph of the function L_g (ΔT_g)](image)

**Figure 3.** Analysis of heat loss specifics.

As we can see in the diagram, the larger the difference \( \Delta T_g \) (or, the larger the vertical temperature gradient), the larger are the heat losses. Thus, vertical gradient must be decreased in order to decrease
heat losses through the ground. It can be achieved by, for example, applying forced indoor air motion in the shelter.

Let us discuss the functional connection of heat losses through external structures $L_{w,r}$ on the proportion \( \frac{\lambda_c}{l} \) (heat transfer coefficient of the material vs. shelter material thickness), i.e., let us discuss a function \( L_{w,r}(\frac{\lambda_c}{l}) \) (at minimum heat losses). In this case, the functional connection is not linear (Figure 3 left).

As we can see from the diagram, for values of up to \( \approx 10 \) of the proportion \( \frac{\lambda_c}{l} \) heat losses increase rapidly, but if \( \lambda_c/l > 20 \), then the heat loss increase is low. Interval \( 10 < \lambda_c/l < 20 \) can be considered as the transition interval. Thus, if the aim is to reduce heat losses, the proportion \( \lambda_c/l \) must be decreased. Evidently, in order to decrease the proportion \( \lambda_c/l \), shelter material thickness must be increased and/or materials with lower heat transfer coefficients \( \lambda_c \) must be used.

Let us analyze the functional connection of heat losses through infiltration $L_{a}$ on the coefficient that characterizes air discharge through the gaps between the shelter’s walls and ground. If this coefficient is expressed as $k_s$, then the function $L_a(k_s)$ should be analyzed. The functional connection is linear, but the function’s diagram does not move through the starting points of coordinates due to the air permeability of the material. Evidently, if the aim is to reduce heat losses, then the coefficient $k_s$ must be reduced. This can be achieved by minimizing gaps, for example. Heat losses can also be reduced by choosing materials with lower air permeability.

![Figure 4. The graph of the function $L_{a}(k_s)$.](image)

Now let us compare the calculated data $L_{\text{min}}=567.7$ W/K and $L_{\text{max}}=1115$ W/K with the values that were obtained using measuring instruments [8, 9], respectively 454 W/K and 766 W/K. Heat transfer coefficients that were taken from the tables have an impact on the final result. Therefore, using the data obtained from measuring instruments, we are going to adjust heat transfer coefficients in the case of minimum heat losses. The same heat transfer coefficient $8.5 \frac{W}{m^2 K}$ was used for shelter walls and roof, both inside and outside. However, warm air collects under the roof surface. Therefore, heat transfer intensity changes because poor air circulation reduces convection. From the expression $L_{\text{min}} = 454 = L_g + L_{w,r} = 137.5 + L_{w,r}$ it follows $L_{w,r} = 454 - 137.5 = 316.5$ W/K. It can be separately calculated $L_{w} = 3.8 \times 60 = 228 \frac{W}{K}$ and thus $L_{g} = 316.5 - 228 = 88.5$ W/K. From this, it follows 1.66 W/m²K. From expression $U_{t} = \frac{1}{\frac{1}{U_{g}} + \frac{1}{U_{w}}} + \frac{1}{U_{r}}$ let us express $U_{t}$. Thus $U_{t} = 2.18$ W/(m²K). The heat transfer coefficient for roof $U_{r} = 8.5$ W/m²K was acquired by means of calculation, but using the measured data, this coefficient can be adjusted, and the value 2.18 W/m²K can be obtained. All other coefficients can be adjusted in a similar manner.

6. Conclusions

There are no any publicly available calculation tools for heat losses estimation in such temporary shelters as light weight tents. The commercially available software such a IDA-ICE can be used for
estimation of thermal comfort and annual energy consumption. However, it doesn’t consider such parameter as liner air permeability. The heat losses through the non-insulated floor also should be addressed in more detailed way. The method of calculations of heat losses from shelters was discussed. Concrete example of calculations was considered. Obtained results were analyzed in order to reduce energy consumption for heating and improve the level of comfort. The calculated data was compared with the values obtained using measuring instruments and adjustment of some coefficients was made.

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