HYBRID COOLING OF A CONTAINER FOR TELECOMMUNICATION EQUIPMENT

HIBRIDNO HLAĐENJE KONTEJNERA ZA TELEKOMUNIKACIONU OPREMU

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The analysis of a typical container for telecommunication equipment was done to determine the potential for passive cooling. It was specified that throughout the year the temperature inside the container should not exceed 45°C. TRNSYS software package was used to analyze the temperature profile and annual cooling energy based on internal heat loads and outside conditions. Outside conditions were simulated using data for a typical meteorological year in Zagreb and Split, published by the Croatian Meteorological and hydrological service. The results showed considerable potential for natural ventilation and heat rejection through the container envelope. Therefore, it has been proposed to use an envelope made solely of aluminum panels, without the insulation. Furthermore, the proposed construction has ventilation grilles and a chimney to enable passive cooling, as well as an axial fan for periods during which natural ventilation is not sufficient. The results suggest that the proposed solution could completely eliminate the need for a conventional system, despite relatively high internal loads from the telecommunication equipment. The estimated annual electricity consumption for cooling is up to 82 times lower than for a conventional container with a split-system (assumed COP = 3).

Key words: *hybrid cooling; telecommunication equipment; energy savings*

Izvršena je analiza tipičnog kontejnera za telekomunikacionu opremu kako bi se odredio potencijal za pasivno hlađenje. Utvrđeno je da tokom cele godine temperatura unutar kontejnera ne sme da bude viša od 45°C. Softverski paket TRNSYS primenjen je za analizu temperaturnog profila i godišnje energije za hlađenje na osnovu unutrašnjih toplotnih opterećenja i spoljašnjih uslova. Spoljašnji uslovi su simulirani korišćenjem podataka za tipičnu meteorološku godinu u Zagrebu i Splitu, koje je objavila hrvatska meteorološka i hidrološka služba. Rezultati su pokazali znatan potencijal za prirodnu ventilaciju i odbacivanje toplote kroz omotač kontejnera. Zbog toga je predloženo korišćenje omotača napravljenog isključivo od aluminijumskih panela, bez izolacije. Takođe, predložena konstrukcija ima ventilacione rešetke i dimnjak koji omogućava pasivno hlađenje, kao i aksijalni ventilator za periode tokom kojih prirodna ventilacija nije dovoljna. Rezultati ukazuju da bi predloženo rešenje moglo u potpunosti da eliminiše potrebu za konvencionalnim sistemom, uprkos relativno velikim unutrašnjim opterećenjima od telekomunikacione opreme. Procenjena godišnja potrošnja električne energije za hlađenje je do 82 puta manja nego za konvencionalni kontejner sa split-sistemom (pretpostavljen koeficijent učinka (COP) = 3).

Ključne reči: *hibridno hlađenje; telekomunikaciona oprema; ušteda energije*

I. Introduction

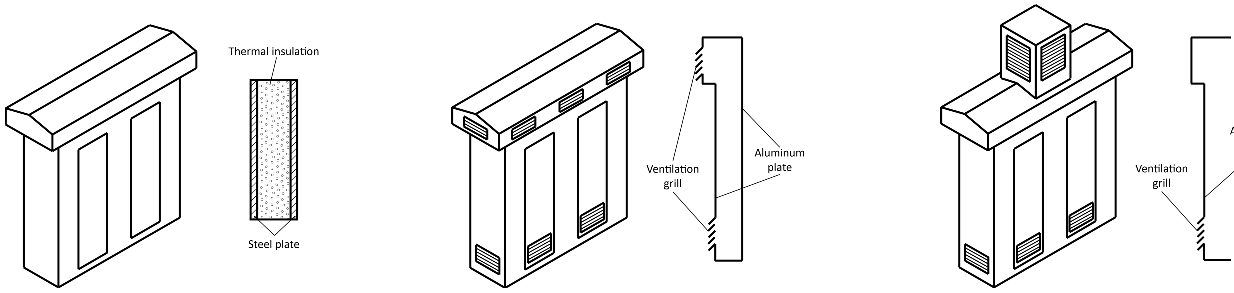
In most applications, the telecommunication equipment is defined as a technology that runs all day, every day, and has high heat dissipation. As a consequence, containers for telecommunication equipment (base stations) usually require cooling all year round in order to maintain the air temperature within a safe range. The most commonly used systems for cooling are split and package cooling systems [9, 8]. Since the electricity consumption for cooling accounts for 25-50% of the total annual electricity consumption of the station [1, 9–11], an energy efficient envelope design and a selection of cooling equipment with adequate control systems offer a wide range of energy saving opportunities. Furthermore, due to the design scalability (the same container design usually gets replicated to many locations and to different sizes of telecommunication equipment), a potential impact of improvements could be substantial.

While some typical container envelopes are described in [10, 1], studies on the envelope design for energy savings are very scarce. Recent studies found in the literature have mainly focused on improvements to mechanical HVAC systems used for container cooling. Zhou *et al.* [11]] analyzed a combined air-conditioner and air-to-air thermosyphon heat exchanger system, in which the thermosyphon heat exchanger uses ambient energy to reduce the electricity consumption. Based on the analysis done for several Chinese cities, in some cases the reported savings were over 50%. Han *et al.* [4] showed that a system that integrates an air-conditioner and a thermosyphon can save 30% energy relative to a conventional air-conditioner. Sundarama *et al.* [8] conducted a field study using a package cooling system that incorporates a phase change material and a two-phase thermosyphon heat exchanger. The heat exchanger was used to absorb the heat dissipated by the telecommunication equipment, to store it as the latent heat, and finally to reject it to the ambient during the night. They reported that the system was capable of fully replacing a conventional air-conditioning system in desert and tropical regions of India. Choi *et al.* [3] experimentally analyzed the cooling performance of a cooling system that was operating in vapor compression mode at high ambient temperatures, and in economizer mode (compressor turned off) at low ambient temperatures. Results showed significant improvements in the Coefficient Of Performance (COP) at low ambient temperatures due to the idleness of the compressor. Sun *et al.* [7] developed a mathematical model for a cooling system that employs a phase change material and a natural cold source. Based on performance analysis for five cities in China, the authors have implied that it is a promising technology, but that more work should be carried out. Although the cooling using ventilation has great potential for energy savings and can achieve a cost reduction of more than 80% [10], only a small number of studies on the subject have been reported. Chen *et al.* [1] proposed the use of ventilation for cooling at low ambient temperatures (ambient air is delivered to the base station by fans), while a conventional air-conditioner would be used for high ambient temperatures. Based on a field study carried out in Guangzhou (China), the reported energy savings were around 49%, and the payback time was less than two years when ventilation was used as part of the cooling strategy. Furthermore, Chen *et al.* [2] proposed a control strategy that improves energy efficiency and minimizes operating costs.

The goal of this research was to evaluate the potential for hybrid cooling of a typical container, and to give design recommendations for future applications. According to the weather data for a typical meteorological year in Zagreb and Split published by the Croatian Meteorological and hydrological service, the highest annual temperature in Zagreb is 36,6^{o}C, and in Split 34,5^{o}C. This is well below the allowable temperature limit inside the container, set at 45°C, and shows considerable potential for passive and/or hybrid cooling. Consequently, three container designs were compared based on their annual energy consumption: the first was a base case modeled according to the current industry practice, while the other two had strategies that promote passive cooling. To the best knowledge of the authors this is the first study that analyzes the effect of a single aluminum plate envelope on energy consumption. In addition, the study proposes a solution for hybrid cooling that does not include split or package systems, not even as a backup cooling energy source.

II. Model description

This paper compares three designs of a container for telecommunication equipment (3,3m in length × 0,8 m in width × 2,4 m in height) based on their annual energy consumption. Design A (base case) represents a typical container with a competelly sealed envelope, made of two steel panels and 5 cm of foam insulation placed between the panels (Figure 1a). The container is cooled with a split-system, needed throughout the year due to relatively high internal loads. Design B shown in Figure 1b has two paths for air circulation in order to promote passive cooling. The first path is a double-skin envelope made of aluminum panels, with ventilation grilles placed in the lower and the upper part of the outer panel. This allows a buoyancy-driven flow inside the envelope, expected to remove heat gains from outside before they enter the container. The second pair of grilles, also placed in the lower and the upper part of the container, allows air to enter the continer through the lower grilles, to mix with the inside air, and to be removed through the upper grilles, solely due to buoyancy. Design C shown in Figure 1c has a single-panel envelope made of aluminum panels. Ten ventilation grilles (0,6 m × 0,2 m) are placed around the lower part of the envelope and four grilles (0,4 m × 0,5 m) are on the chimney. The chimney is 0,6 m high and is placed in the middle of the roof to enhance the air flow movement around the equipment. An axial fan is placed inside the chimney to enhance air circulation when natural ventilation is not sufficient. Although it introduces additional pressure losses and, therefore, reduces the potential for natural ventilation, the fan can significantly reduce the need for conventional cooling, as will be shown later in the paper.



(a) (b) (c)

Figure 1. Container geometry for a) Design A b) Design B and c) Design C

TRNSYS [5] software package was used to calculate the thermal behavior and the cooling energy consumption for each hour of the year. The only source of internal loads was the equipment, modeled as a constant sensible gain of 2,2 kW. Outside temperatures and solar gains were simulated using the data for a typical meteorological year in Zagreb and Split, published by the Croatian Meteorological and hydrological service. It is assumed that the conventional cooling employs a split-system with a Coefficient Of Performance (COP) of 3, and that the axial fan (in Design C) has an airflow rate of 1000 m^3/h and electricity consumption of 30 W. All three designs were analyzed using the same internal temperature set point of 45°C, as recommended by the manufacturer of telecommunication equipment. Heating was not considered since the container requires cooling throughout the year as a result of high internal loads.

Because of their envelope design, Design B and Design C have considerable potential for passive cooling using natural ventilation. It is expected that the wind-driven flow will have a positive effect on passive cooling. However, it is difficult to predict the direction, intensity and duration of the wind without detailed measurements on a specific location. Due to the lack of these data, the wind-driven flow was not taken into account, and only buoyancy-driven natural ventilation was considered in the presented analyses. For the buoyancy-driven flow, the airflow is a strong function of the temperature difference (T_{inside} - $T_{outside}$), grille area (A), and the height between the lower and upper grilles (H):

$$V = (AC_d)_{eff}\sqrt{2gH\frac{T_{inside}-T_{outside}}{T_{inside}}} \quad (1)$$

where

$$(AC_d)_{eff} = \sqrt{\frac{1}{\sum_{i=1}^{n}\frac{1}{A_i C_{d,i}}}} \quad (2)$$

The discharge coefficient, C_d, accounts for pressure losses on the elements that act as airflow resistance. Its value is between 0 and 1, depending on the element type, geometry and Reynolds number. The values of discharge coefficients of grilles and fan used in this analysis are from [5].

In the steady-state, the cooling rate delivered to the container by natural ventilation needs to be equal to sensible loads (heat loads from the equipment and from outside):

$$Q_{heat\_load} = V\rho c(T_{inside} - T_{outisde}) \quad (3)$$

Equation 1 and Equation 3 create a system of coupled equations since the airflow is a function of the inside temperature (Equation 1) and the inside temperature is a function of the sensible loads and airflow (Equation 3). In this research, the system of coupled equations was iteratively solved for the airflow and inside temperature using a connection between MATLAB and TRNSYS.

III. Results and discussion

The objective of the first analysis was to evaluate the annual performance of three different envelopes. To exclude the influence of other design parameters, this analysis assumed that the outside air does not enter the container in any of the three designs (natural ventilation in the container was neglected in Design B and C). Design A (base case) had a sealed envleope, made of two steel panels and 5 cm of foam insulation; Design B had a double-skin envelope to promote air circulation inside the envelope; Design C had an envelope made of an aluminum panel without insulation. In general, insulation has a positive effect on energy reduction since it reduces the impact of outside conditions on the internal environment. However, in this specific case in which the internal heat gains are constant and high relative to the outside heat gains, the envelope should be designed to enhance heat rejection, especially in winter and shoulder seasons. A negative impact of insulation can be seen when the performance of the envelope in Design A (Figure 2a) and Design C (Figure 2c) are compared. The simulation results show that the container with the insulated envelope requires cooling each hour of the year, and that the inside temperature is at the upper temperature limit throughout the year (Figure 2a). On the other hand, the container with the uninsulated envelope consumes 3,7 times less electricity for cooling in Zagreb and 2,7 times less in Split (assuming the COP of 3), and has lower inside temperature most of the year (Figure 2c). For the envelope in Design B, the results suggest that the buoyancy force would not be sufficient for an effective air flow inside the double-skin envelope due to local pressure drops and a small height between the grilles. For the worst case scenario, the air inside the double-skin envelope would be still, and would act as an insulation layer. The required cooling energy and inside air temperature profiles for the worst case scenario (Figure 2b) show that the envelope in Design B has an inferior performance compared that of the envelope in Design C; therefore, Design B was discarded from any further analysis.

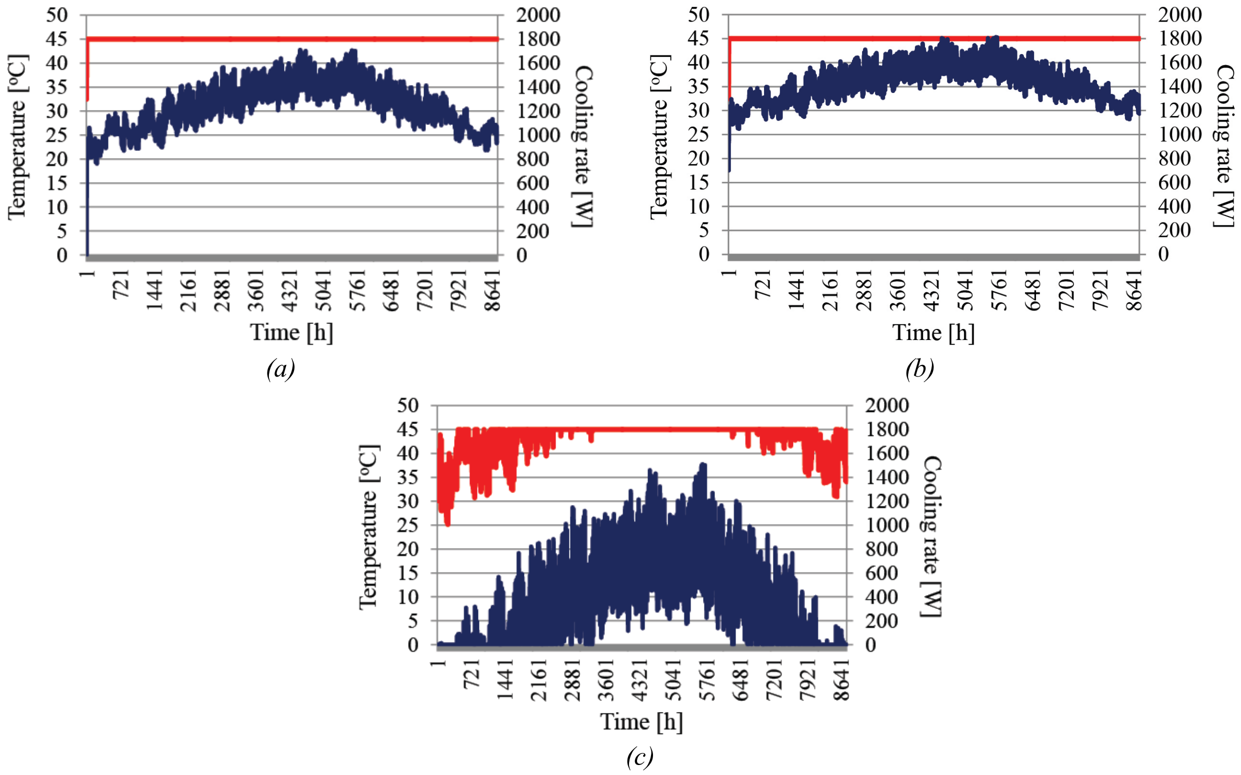


Figure 2. Inside air temperature (red) and required cooling rate (blue) for the envelope in (a) Design A, (b) Design B, and (c) Design C (for Zagreb)

The second analysis evaluated the impact of using a fan on the annual electricity consumption for cooling. Only Design C was considered since it had a superior envelope performance relative to Design B, as shown in the previous analysis. Simulations were carried out assuming an axial fan that operates at 1000 m^3/h, and has the electricity consumption of 30 W, as specified in the manufacturer's data. A comparison between the container without the fan (Figure 3a) and with the fan (Figure 3b) shows that the use of fan can completely eliminate the need for conventional cooling. Moreover, the inside temperature shown in Figure 3b was well below the specified temperature limit during most of the year. For the worst case scenario, if one would completely neglect natural ventilation, it is estimated that the fan would work about 250 days annually in Zagreb and 320 days in Split. It is recommended to place the fan in the middle of the container, just below the chimney, so that it can efficiently remove heat from the equipment and achieve more homogeneous temperature profile inside the container.

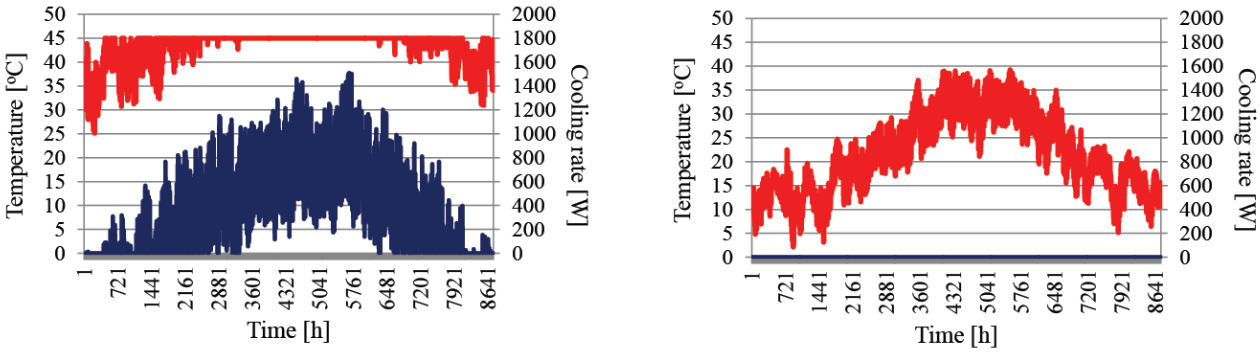


Figure 3. Inside air temperature (red) and the required cooling rate (blue) for Design C
(a) without the use of a fan, (b) with the use of a fan (for Zagreb)

According to meteorological data, Zagreb and Split have good potential for passive cooling, which was partially utilized using the uninsulated envelope to improve heat rejection to the outside. In addition, Design C has the chimney and grilles to promote buoyancy-driven natural ventilation. Wind-driven natural ventilation was neglected due to unreliable wind data for the specific location under consideration. However, it is expected that the wind-driven flow will enhance the natural ventilation potential presented here. Although an axial fan has a strong negative effect on natural ventilation as a result of additional flow resistance, the results demonstrated that natural ventilation alone is not sufficient to replace conventional cooling, and that the fan cannot be eliminated. Nevertheless, the use of buoyancy-driven natural ventilation resulted in the reduction in fan operating days from 250 to 61 day in Zagreb and from 320 to 110 days in Split.

Figure 4 shows the impact of all proposed strategies on the annual reduction in electricity consumption for cooling in climate conditions in Zagreb. The uninsulated envelope reduced the electricity consumption for cooling from 3610 kWh (base case) to 980 kWh, the use of axial fan allowed a further reduction to 180 kWh, and the use of fan and natural ventilation (NV) to final 45 kWh, which is 82 times less energy than the base case. The results are very similar for climate conditions in Split, with 3885 kWh for base case, 1400 kWh with the uninsulated envelope, 230 kWh with the use of fan, and 80 kWh with the use of fan and natural ventilation, which is 49 times less than the base case.

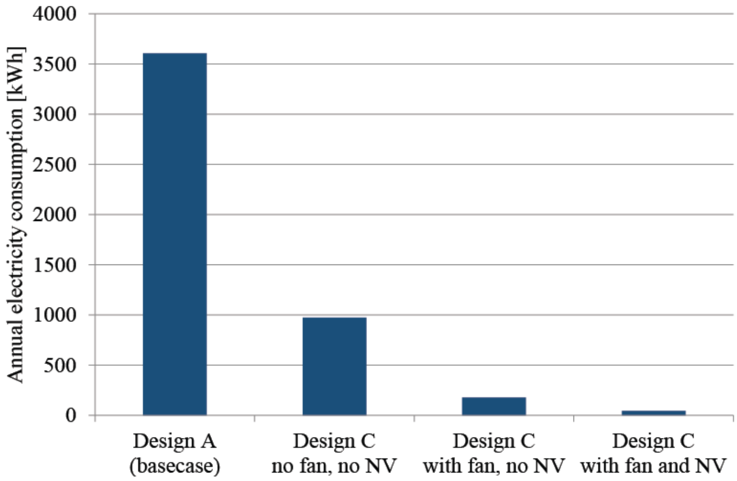


Figure 4. Reduction in annual electricity consumption for cooling using the proposed Design C

IV. Conclusion and future work

The research presented in this paper evaluated the hybrid cooling potential of a typical container for telecommunication equipment, and gave design recommendations for future applications. Great potential for passive cooling was exhibited due to a relatively mild climate (especially in shoulder seasons), as well as steady, high internal loads from the equipment. This potential was exploited and the envelope and the cooling system design were improved.

The first strategy was the use of a single-skin, uninsulated envelope that promotes heat rejection to the outside environment and hence, reduces cooling energy. The simulation results showed that the container with the proposed envelope consumed 3,7 times less electricity for climate conditions of Zagreb, 2,7 times less for those of Split, and had lower inside temperature throughout the year relative to the base case with the insulated envelope. Furthermore, the single-skin envelope also showed better performance relative to the double-skin envelope, mainly because the small height between the grilles and relatively high resistances prevent efficient air circulation inside the double-skin envelope.

The second strategy was the use of an axial fan characterized by low electricity consumption. It was demonstrated that the use of the fan completely eliminated the need for conventional cooling, and reduced the electricity consumption by 5,4 times for climate conditions of Zagreb and 6,1 times for those of Split relative to the container with conventional cooling. Assuming that the fan is the only means of cooling, it is estimated that it would operate about 250 days annually in Zagreb and 320 days in Split. The proposed fan placement was in the middle of the roof in order to improve air mixing and unification of the temperature inside the container.

The third strategy utilized buoyancy-driven natural ventilation, for which the grilles with large free area were placed on the bottom of the container and on the chimney. The use of the natural ventilation resulted in the reduction of fan operating days from 250 to 61 days in Zagreb and from 320 to 110 days in Split.

With all the strategies combined, the proposed design consumed 82 times less energy for climate conditions of Zagreb and 49 times less for those of Split relative to the base case. As a result, the operating cost for cooling is negligible, not only relative to the conventional cooling system, but in absolute amount as well. To the best knowledge of the authors, this is the first solution that entirely relies on the use of the natural ventilation and the low-consuming axial fan, completely eliminating conventional cooling systems (such as split or package systems).

Based on the design recommendation, prototypes were built and allocated on several locations in Croatia. The initial feedback suggests that the proposed design has led to noticeable reduction in investment costs and in construction time, both of great importance to the telecommunication company. The future work will include field testing of the prototype, with measurements of the air temperature inside the container, as well as measurements of the fan operating hours. Furthermore, axial fans with a larger free area and therefore lower resistance will be tested with the goal of enhancing the buoyancy-driven flow.

Acknowledgments

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Nomenclature

Symbol	Description	Unit
A	surface area	m^2
C	coefficient	-
c	specific heat	J/(kgK)
g	standard gravity (= 9,80665)	m/s^2
H	height	m
Q	heat flux	W
V	volumetric flow rate	m^3/s
T	temperature	K
ρ	air density	kg/m^3
Subscripts		
eff	effective	
heat_load	sensible heat load	
inside	indoor value	
outside	outdoor value	

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