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Performance of a free-air cooling system for telecommunications base stations using phase change materials (PCMs): In-situ tests

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HIGHLIGHTS

- A free-air cooling system that uses PCMs was developed for TBSs.
- PCM stores natural cold energy and release this energy into TBSs.
- The operation of A/C is shortened, resulting in energy savings.
- The largest energy savings ratio of this unit was 67% with an average value of 50%.
- The average annual operating time that this unit replaced traditional A/C use was 83%.

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ABSTRACT

A free air cooling system that combines phase change material (PCM) with a natural cold source (i.e., cold air) was developed to reduce the space cooling energy consumption in telecommunications base stations (TBSs). Outside cold air, instead of air conditioning system was used to remove heat in the TBSs. In addition, a PCM technology was adopted to improve the mismatch between energy demand and supply on the electric grid. The proposed system was intended to operate in conjunction with existing air conditioning units within each TBS. Consequently, the running time the air conditioning units was reduced, resulting in energy and demand savings. A full scale prototype, herein referred to as *latent heat storage unit* (LHSU), was designed, built and tested in TBSs located in five different climatic regions in southwest and eastern China during different seasons. In addition, a mathematical model was developed to simulate the operation of the proposed LHSUs. Energy savings ratio (ESR) was used as the criterion to evaluate LHSU's energy savings. The estimated average annual ESR in five climatic regions was approximately 50%, with a maximum value of 67%. The average percent running time in which the LHSU replaced the operation of conventional air conditioners was 82.6%, with values surpassing 75% in four of the five cities, and one city achieving a value of almost 100%.

1. Introduction

China is the world's largest mobile phone market. As of the first half of 2013, the number of mobile phones exceeded 1.15 billion [1]. With this vast amount of signal traffic, the thermal management of telecommunications base stations (TBSs) has become exceedingly challenging. TBSs are small buildings located in fixed locations, where reception and transmission equipment is housed. This equipment generally consists of electronic and heat generating hardware used to handle signal traffic between mobile phones and network subsystems. As the numbers of these stations and network equipment continue to increase, so is the amount of electrical energy needed to keep their indoor air at specified temperatures and relative humidity [2,3], which is critical for the proper functioning of electronic equipment. The electrical energy which is consumed by the air conditioners that condition the air in these stations accounts for 30–50% of the total energy used in TBSs [4]. This is the case because for most part these air conditioners work 24 h per day all year round. Therefore, the space cooling of these

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Nomenclature

A	area (m^2)
c	specific heat (kJ/kg/°C)
d	diameter (m)
G	volumetric flow rate (m^3/h)
Δh_m	latent heat of fusion (kJ/kg)
I	electricity consumption (kW h)
l	length (mm)
Nu	Nusselt number
P	Power (W)
Pr	Prandtl number
Q	heat transfer rate (W)
r	radius (mm)
Re	Reynolds number
T	temperature (°C)
ΔT	temperature difference (°C)
V	volume (m^3)

Abbreviations

ESR	energy savings ratio (%)
LHSU	latent heat storage unit
LMTD	log mean temperature difference
PCMs	phase change materials
TBS	telecommunications base station

Greek symbols

α	convective heat transfer coefficient (W/m^2 °C)
γ	melting or solidification constant
ε	relative error (%)
λ	thermal conductivity (W/m °C)
ρ	density (kg/m^3)
τ	running time (h)
$\%\tau$	percent running time (%)

Subscripts

a	air
aw	between air and water
bc	boundary condition
cl	cooling load
con	conventional air conditioner
cp	copper pipe
ec	energy charging process
ed	energy discharging process
f	fan
fa	fresh air process
fin	final
in	indoor
ini	initial
m	phase change material
out	outdoor
p	pump
s	solid
w	water
wm	between water and PCM

Superscripts

ed	energy discharging process
in	inlet
n	Prandtl number exponent in Dittus–Boelter equation (0.3 for cooling and 0.4 for heating)
out	outlet
t	test

stations is considered a primary target for energy management and conservation [3]. Of the technologies based on the use of natural cold energy, free air cooling has drawn significant attention as an effective approach to reduce the space cooling energy use in TBSs [5,6]. However, the intermittent and unpredictable nature of the natural cold energy poses major challenges for its implementation. A possible solution is the use of a thermal storage component to correct the gap between energy demand and supply [7].

Kuznik and Virgone [8] and Zhou et al. [9] pointed out that phase change materials (PCM) could decrease temperature fluctuation and reduce energy consumption in buildings. As a result several thermal energy storage systems have been developed. For example, Halawa and Saman [10] and Gracia et al. [11] provided information for the development of air based phase change thermal storage units, where air passed through PCM slabs. Their theoretical and parametric studies highlighted first order parameters for the design and operation of these units. Mahmoud et al. [12] developed six heat sinks with six types of PCMs to cool electronic devices. The heat sink with single cavity inserting honeycomb inside or filled with PCM with a low melting temperature (29 °C in their research) showed the best performance in terms of temperature control. Darkwa and Su [13] simulated microencapsulated PCM systems in rectangular, triangular and pyramidal configurations. It was concluded that microencapsulated PCM particle distribution enhanced the effective thermal conductivity by approximately 10 times, but reduced the energy storage capability by 48%. Therefore, other methods for enhancing both the thermal conductivity and energy storage capability had to be developed. To solve the heat transfer problem within the energy storage system, Tay et al. [14,15] and Amin et al. [16] proposed the effectiveness-NTU method to characterize tube-in-tank and PCM encapsulated in spherical thermal energy storage systems. Correlations were established to predict the average thermal capacity for the systems. Longeon et al. [17] studied the heat transfer mechanisms that take place during phase transition processes in annular latent storage units. Based on the above and in combination of the free-air cooling theory and the above heat transfer mechanism, Liao et al. [18] developed a free-air cooling system that uses latent heat storage in combination with a natural cold source (i.e., outside cold air) to serve alongside existing air conditioning systems in which case outside cold air is directly used to cool the interior space of TBSs. The excess cold energy that remains in the cold air is stored in the PCM, which is then released into the conditioned space when outside cold air is not available. Therefore, the operation of conventional air conditioners can be shortened resulting in significant energy savings. A prototype unit, herein referred to as *latent heat storage unit* (LHSU), was designed, built, and experimentally verified in an enthalpy difference laboratory. The annual adjusted energy efficiency ratio of this unit was between 11.98 W/W and 14.91 W/W, which varied with outdoor and indoor air temperatures [19].

To evaluate the application of this technology in TBSs, in-situ tests of the energy savings potential of the free-air cooling system were conducted in five different climatic locations during different seasons. Five cities from around China with a wide range of climatic conditions were selected, including Shenyang (severe cold region), Zhengzhou (cold region), Kunming (mild region), Guangzhou (hot summer and warm winter region), and Changsha