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Model-based energy monitoring and diagnosis of telecommunication cooling systems

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ABSTRACT

A methodology is proposed for on-line monitoring of cooling load supplied by Telecommunication (TLC) cooling systems. Sensible cooling load is estimated via a proportional integral controller-based input estimator, whereas a lumped parameters model was developed aiming at estimating air handling units (AHUs) latent heat load removal. The joint deployment of above estimators enables accurate prediction of total cooling load, as well as of related AHUs and free-coolers energy performance. The procedure was then proven effective when extended to cooling systems having a centralized chiller, through model-based estimation of a key performance metric, such as the energy efficiency ratio.

The results and experimental validation presented throughout the paper confirm the suitability of the proposed procedure as a reliable and effective energy monitoring and diagnostic tool for TLC applications. Moreover, the proposed modeling approach, beyond its direct contribution towards smart use and conservation of energy, can be fruitfully deployed as a virtual sensor of removed heat load into a variety of residential and industrial applications.

1. Introduction

In recent years, the increase in CO_2 concentration in the atmosphere, due to a high consumption of fossil fuels, has resulted in dramatic greenhouse effect rise, with consequent negative impact on average temperatures worldwide, which in turn has enhanced the occurrence of severe climatic phenomena, such as floods, droughts and hurricanes. Therefore, people are paying particular attention to energy saving policies, as well as to enhancing the recourse to renewable energy sources worldwide.

Following the European Council held on March 8–9 2007, precise targets about reducing greenhouse gas emissions were decided. Particularly, the commitments made by the European Council for 2020 [4] consist of cutting greenhouse gases emissions by 20%, reducing energy consumption by 20%, and achieving 20% share for renewable primary energy sources within the entire Union (i.e. the so called 20-20-20 target).

The Information and Communications Technology (ICT) sector is nowadays responsible for a significant share of world energy consumptions, thus justifying the expectation of a substantial contribution to be provided by ICT companies to achieve such targets [23]. The ICT companies are particularly required to undertake several actions in order to reduce their energy use from an efficiency point of view, such as carefully investigating where and how consistent is the room for improvement in terms of energy conservation and optimal energy management [18], as well as exploring new ways and means (e.g. solar cells [35] and thermoelectricity [38]) that are suitable to well comply with sustainable development constraints. Therefore, many of them have started monitoring their own energy absorption with dedicated sensors [25,34]. In both data centers and switching rooms there are direct consumptions, due to the absorption of DC current by the electronic equipment, and indirect ones, essentially due to the cooling systems needed to remove the heat power dissipated by the electronic components. In most severe conditions (i.e. hot weather), almost half of the energy used by data centers and switching rooms is absorbed by cooling systems, whose use is necessary because electronic components must operate within assigned ranges of temperature and humidity [6]; [2]. Therefore, it is agreed that optimal energy management [24,32] and real time monitoring [5] of both air free coolers (FCs) and air handling units are to be accurately addressed.

To tackle the above mentioned issues, i.e. need for real-time

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Nomenclature

Acronyms

AC	Alternating current
AHU	Air handling unit
DC	Direct current
EER	Energy efficiency ratio
FC	Free cooler
ICT	Information and communications technology
TLC	Telecommunication
WSN	Wireless sensor network

Roman symbols

BP_{coeff}	By pass coefficient (s)
c_p	Specific heat (J/kgK)
H	Global coefficient of heat exchange (W/K)
K	Total heat capacity, (J/K)
K_p	Proportional parameter of PI controller (W/K)
K_i	Integral parameter of PI controller (W/K)
K_u	Critical value of PI controller (W/K)
$\dot{m}$	Mass flow (kg/s)
P	Electrical power, (W)
P	Pressure (Pa)
$\dot{Q}$	Cooling load (W)
r_0	Specific latent heat of condensation at 273 K (J/kg)
T	Time, (s)
t_{AHU}	Air handling unit constant time (s)
t_{off}	Time when AHU turns off (s)
t_{on}	Time when AHU turns on (s)
T	Temperature, (°C)
$T_{AHU,HE,off}$	Heat exchanger's temperature when AHU turns of (°C)
$T_{AHU,HE,start}$	Heat exchanger's temperature when AHU turns on (°C)
$T_{dew\ point}$	Dew point (s)
X	Specific humidity (/)

Greek symbols

Δ	Change
Φ	Relative humidity (/)
η	Efficiency (/)

Subscripts

AHU	Air handling unit
Ave	Average
CH	Chiller
Ext	External/outside
FC	Free cooler
HE	Heat exchanger of AHU
In	Room inlet
L	Latent
S	Sensible
TLC	Telecommunication

monitoring of energy consumptions and reducing the impact of cooling systems adsorption, Telecom Italia has recently developed a tool based on Wireless Sensors Networks (WSNs), for remote monitoring, auditing and controlling active (i.e. for powering telecommunication equipment) cooling energy consumption in buildings. Particularly, ZigBee-based WSNs [9] were massively deployed in main Telecom Italia central offices, so as to monitor most relevant environmental data, such as external and internal temperatures, humidity and light intensity, as well as TLC equipment energy consumption. Three main sensor typologies were deployed in Telecom central offices: (i) temperature, humidity and light (THL), (ii) AC current and (iii) DC current. While (i) type sensor enables the monitoring of actual room temperature, sensors (ii) (Rogowski) and (iii) (Hall Effect sensor chips) allow the detailed energy consumption monitoring for TLC equipment and CC system. The monitoring system was conceived in such a way as to comply with the following requirements: the average cost of each measuring point should be kept as low as possible; the monitoring system must have negligible installation and maintenance costs; sensor node are battery powered and the replacement time should be long enough; sensor node should be easily switched on and off and added or removed from the WSN; data are collected and made accessible via an easy-to-use web application.

The wide availability of data provided by the above mentioned WSN-based monitoring platforms can enable the development of advanced model-based methodologies and procedures, aimed not only at improving energy efficiency, but also at discovering unnecessary consumption ahead of time, through dedicated building diagnosis procedures [13]. Model-based analyses were shown to be effective to define and verify innovative monitoring metrics for airflow and cooling performance of data-centers [12], as well as for assessing thermal management system efficiency via exergy analysis [27]. The authors themselves have already proposed mathematical tools aimed at optimizing FC and AHU energy management [29], as well as at introducing new monitoring and diagnostics-oriented model-based metrics [30], both at single TLC and entire central office level. As a follow-up of the previous studies, the present article proposes a further exploitation mean of available modeling tools, namely to infer useful information on cooling performance via model inversion, so as to enable the estimation of unmeasurable input variables. Specifically, TLC room cooling performance monitoring entails estimating effective heat removed to calculate key energy efficiency metrics, such as the Energy Efficiency Ratio (EER). Such an estimation can be either performed by directly inverting room thermal dynamics model, provided that external and inner room temperature measurements are fairly noise-free and model uncertainties limited, or by developing suitable input estimators. Indeed, the latter solution is highly recommended when significant noise or modeling uncertainties are expected, as deeply discussed by Refs. [31] and [17]. The former contribution emphasized input estimators potentialities for automotive engine control, whereas [17] proved their applicability also for thermal sensors signal reconstruction. Further contributions were proposed on the application of input estimation as a particular class of observers that can tackle issues of practical interest. Among others [36], proved the suitability of Proportional Integral (PI) observers for Takagi-Sueno fuzzy models that depend on unmeasurable inputs and decision variables. With particular regard to PI-based input observers [3], developed an interesting comparative analysis between purely integral action and proportional integral input estimation, highlighting how the former one ensures filtering out measurement noise, whereas the proportional term addition also guarantees appropriately treating unavoidable modeling uncertainties. Therefore, the latter suggestion was followed in the current work, with the specific aim of developing an automatic input estimator that relies on easy to measure data (e.g. room and