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A simplified method to evaluate the seasonal energy performance of water chillers

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ABSTRACT

The calculation or certification of the energy consumption of buildings equipped with refrigerating or heating units operating on vapour compression cycles requires an accurate evaluation of their performance at full and part load under different operating conditions. Refrigeration systems simulation models are normally useless because of the large amount of input data required for a full characterization.

A simplified numerical method for the performance prediction of vapour compression heat pumps and chillers is here presented, based only on performance data at the nominal rating conditions. The proposed procedure was validated against experimental data of different packaged air-cooled water chillers, operating on scroll compressors. In chillers full load conditions approximately 89.5% and 92.1% of the predicted EER and cooling capacity values respectively are consistent with the measured data within a relative deviation of ±10%. Simulation results are in good agreement with the experimental ones also if the experimental seasonal energy efficiency ratio, $SEER_{on}$, described in the European standard draft prEN 14825, is considered. The deviations range from −3.2% to +5.1%. The proposed mathematical model appears to be a reliable tool to be implemented into dynamic building-plant energy simulation codes or into building energy certification tools.

1. Introduction

Efficient use of energy is one of the main strategic measures not only for the preservation of fossil energy resources but also for the abatement of air pollution and the slowing down of anthropogenic climate change. The requirement of primary energy to cool and to heat buildings is an important part of the overall energy consumption in Western countries, summing up to about 40% of the U.S. and European global energy consumption. According to EECCAC – Energy Efficiency and Certification of Central Air Conditioners project, the cooled area in 2010 in Europe will be 2200×10^6 m^2. These expectations are confirmed by the ever growing number of chillers sold in European Union (EU) every year In a "Business As Usual" growing scenario the electricity consumption related to cooling loads was around 51 TWh in 2000, becoming 95 TWh in 2010. CO_2 emissions would rise from 18×10^6 t in 2000 to 33×10^6 t in 2010 [1]. As a consequence, the electrical end-use and the energy efficiency of central air conditioning systems are becoming an important issue for the European Commission.

In November 2008 the European Commission adopted a proposal for a new Energy Performance of Building Directive (EPBD). This "recast" EPBD will come into force in 2010. Its structure remains similar as the 2002 version but the minimum energy performance requirements of buildings will be pursued more efficiently. In order to certify the energy consumption of a building equipped with a vapour compression refrigerating or heating unit, the seasonal efficiency must be more correctly evaluated. In fact many of the potential energy savings associated to building heating and cooling operations are related to the systems optimisation under part load conditions [2,3]. Nominal rating conditions, in fact, are not representative of the seasonal equipment average operating conditions. Energy efficient refrigeration units have to be designed not only considering nominal operating conditions but also taking into account part load operations. Part load based design improves seasonal efficiency considering real life variations of both building thermal load demand and heat exchangers secondary fluid temperatures.

EN ISO 13790 standard [4] on the energy performance of buildings contains a calculation method of the monthly energy use for space heating and cooling under steady-state conditions

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Nomenclature

A	heat transfer surface [m^2]
C_c	cycling degradation factor [-]
COP	heat pump energy efficiency [−]
c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
d	heat exchanger hydraulic diameter [m]
EER	chiller energy efficiency [−]
fq	compressor or fan capacity partialization rate [−]
h	enthalpy [J kg^{-1}]
hd	heat dissipation factor [−]
k	transmittance correction coefficient [−]
$\dot{m}$	mass-flow rate [kg s^{-1}]
N	compressors number
n	circuits number
n_f	fans number
P	power consumption [W]
PLF	part load factor [−]
PLR	part load ratio [−]
p	pressure [Pa]
Q	thermal power [W]
Re	Reynolds number: $\mathrm{Re} = \frac{\dot{m} \cdot d}{S \cdot \mu}$ [−]
S	cross sectional area [m^2]
T	temperature [°C]
U	overall heat transfer coefficient [W m^{-2} K^{-1}]
UA	thermal transmittance [W K^{-1}]
$\dot{V}$	swept volume per time unit [m^3 s^{-1}]
w_P	partialization power consumption correction factor [−]
w_Q	partialization cooling capacity correction factor [−]

Greek letters

α	heat transfer coefficient [W m^{-2} K^{-1}]
Δ	difference [−]
η_{el}	electric efficiency [−]
η_{is}	isentropic efficiency [−]
η_v	volumetric efficiency [−]
θ	logarithmic mean temperature difference [K]
ρ	density [kg m^{-3}]

Subscripts

aux	auxiliary
c	condenser/condensation
D	design
e	evaporator/evaporation
k	compressor
load	actual load condition
r	refrigerant
SC	subcooling
SH	superheat
sf	secondary fluid

Symbols

^	referred to EN 12900 test conditions

hypothesis. In alternative the calculation of the building thermal load can be made using dynamic procedures [5]. Whichever is the chosen method, the assessment of the primary energy consumption and of the average performance of the plant is a fundamental step for the correct evaluation of a building energy performance. Normally this calculation is carried out at steady-state conditions for time intervals equal to the time step of the building thermal load calculation method (one month for the EN ISO 13790 and usually 1 h for dynamic simulation methods) [6]. As far as vapour compression systems are concerned, this procedure consists of two steps. At first, on the basis of the actual temperature and mass-flow rate values at the unit heat exchangers, the calculation of the cooling or heating capacity and of the system efficiency in terms of EER (energy efficiency ratio defined as the ratio of cooling capacity and total power consumption, fans included) at full load working conditions has to be done. Second, the effects of cooling or heating capacity control on the refrigeration unit performance have to be evaluated. The part load ratio (*PLR*) can be defined as the ratio of the building thermal load to the machine full capacity. The part load influence is taken into account by multiplying the full load EER by a part load factor (*PLF*).

The data necessary for the application of this procedure are often partly or completely lacking. The system full load performance as a function of the temperature and mass-flow rate values at the unit heat exchangers are sometimes present in manufacturer data sheets, but in most cases only nominal rating conditions are reported. As already pointed out by Bettanini et al. [3], machines part load performance are seldom supplied. A *PLR* independent and constant value of the part load factor can be obtained if a manufacturer data sheet reports the ESEER index, namely the European Seasonal Energy Efficiency Ratio, as defined by Eurovent [7]. *PLF* can be defined directly as the ratio of the ESEER to the machine EER at nominal rating conditions. In fact the ESEER index is calculated as a weighted average of EER at four different part load conditions and secondary fluid temperature values. European committee for standardization (CEN) TC113/WG7 is working to develop a similar European standard for rating seasonal performance indices of all HVAC equipment. In November 2009 a draft standard prEN 14825 was released and submitted to the CEN public enquiry [8].

Bettanini et al. [3] demonstrated that an improved definition of *PLF*, namely expressing the part load factor as a function of *PLR*, can greatly improve the accuracy of the building primary energy consumption. These authors suggested the use of Italian standard UNI 10963 *PLF* calculation method [9]. Nevertheless this procedure requires additional experimental tests on the refrigeration unit and should be extended to step capacity machines.

In this paper a simplified numerical method for the performance prediction of vapour compression systems is presented. The mathematical model predicts the unit cooling or heating capacity and power consumption at part load conditions and at different heat exchangers secondary fluids inlet temperatures only on the basis of the performance data at the nominal rating conditions. The unit compressors performance data, together with thermal capacity control and simple refrigerant circuit information, are also needed. The proposed procedure is validated against experimental data of packaged air-cooled water chillers, operating on scroll compressors. Single compressor, double compressors and inverter driven units are tested.

The paper is organized as follows. In Section 2 the mathematical model is presented. Full and part load calculation methods are detailed. In Section 3 the tested chillers are outlined and the capacity control strategies are detailed. In Section 4 the experimental test facilities used to rate the chillers are described. Testing procedures are also detailed. In Section 5, units experimental part load performance and seasonal energy ratios are presented and