Carbon emissions
Comparative study of HVAC systems in hospitals
Chilled beams and fancoils

Filipe Miguel Fernandes Ventura

Extended Abstract

Supervisors: Professor Tiago Morais Delgado Domingos
Professor Jorge Alberto Gil Saraiva

October 2011
Carbon emissions
Comparative study of HVAC systems in hospitals
Chilled beams and fan coils

Filipe Ventura

ABSTRACT

Climate change is a serious threat to the global environment. Climate is influenced by changes in atmospheric concentrations of greenhouse gases (GHGs) that trap infrared radiation from the Earth's surface. The international commitments regarding GHG emission levels for the European Union are based on the Kyoto Protocol, aimed at a reduction of 8%, followed by the 20% reduction goal proposed by the Climate and Energy Package and the long-term goal, set in the G8 summit in Italy, of 80% reduction of GHG emissions in 2050 (compared to the reference year 1990).

This dissertation aims to develop simple tools which, in an expedite way, allows the determination of carbon emissions of Heat, Ventilation and Air Conditioning (HVAC) systems in order to make a comparative analysis of systems and assess the possibility of reducing emissions.

These tools were applied to the project for an inpatient ward of a hospital to be built in Faro so, considering what seems to be the current expansion of the HVAC market in healthcare, two systems were considered, fan coils and chilled beams, as case studies. Given the contribution of the HVAC equipment’s energy consumption, equal to about 95% of global carbon emissions, the importance of developing an expedite tool to estimate the annual thermal needs and equipment’s electricity and gas energy consumption should be emphasized. It is also worth noting the introduction in this dissertation of the Humidity-Day original concept, that estimates, alongside and in analogy to the Degree-Day, the dehumidification and humidification annual needs.

Comparing the results, it was found that the choice of a chilled beam system instead of a fan coil system allows a reduction in annual electricity consumption by 18,5% and 19,3% in gas consumption, the annual reduction of 18,6% in primary energy consumption, and the reduction in carbon emissions by 20% during the analyzed period of 30 years.

INTRODUCTION

The Kyoto Protocol, signed in 1997, is one of the most important international legal instruments in the fight against climate change, which marked the beginning of a set of international commitments to reduce emissions of GHG, in particular, with the creation of EU directives, such as the European Directive on the Energy Performance of Buildings (EPDB), Directive 2002/91/EC, and its recent recast in the form of Directive 2010/31/EU, following the Climate and Energy Package, among others.

To compare the impacts of different GHG, it is used, as a reference, the GWP with respect to CO2, adopting the designation of CO2 equivalent, which can also be converted in terms of carbon equivalent, through ratio of its molar mass.

The reduction of carbon emissions and the emissions trading system (ETS) are emerging issues that will lead to penalties in the future, for failure to comply certain targets by Member States. In this
sense, there is a growing need, by all business sectors, for measuring and assessment of systems or products carbon emissions.

The determination of direct and indirect emissions implies a system or product decomposition in its life cycle different stages, in terms of manufacturing of materials and supplies, including raw material extraction and processing, cargo and people transport, energy consumed during operation, end of life disposal, among others.

Regarding buildings, it is important to assess which systems provide the best indoor conditions, and also proceed to balance environmental improvements and their overall costs, so their evaluation through a tool that calculates carbon emissions is a competitive advantage for the decider.

This project aims to develop simple tools which, in an expedite way, allow the determination of carbon emissions from HVAC systems in order to make a comparative analysis of systems and assess the possibility of reducing emissions.

The application of these tools was performed on an inpatient ward of an hospital building to be built in Faro, over what seems to be the current expansion of the HVAC market in healthcare (ACSS, 2010), were considered two systems, fan coils and chilled beams, as case studies. It was also intended to further evaluate the factors which has the highest contribution in reducing carbon emissions.

**HVAC SYSTEMS**

The analysed terminal units are part of an HVAC centralised air-to-water system (Roriz, 2006), with a chiller for chilled water production and a gas-fired boiler for hot water production, and an Air Handling Unit (AHU) that introduces primary air into the terminal equipment, which in turn have chilled and hot water coils, supplied by electric pumps.

**Fan coil (FC)** - Fan coil units are compact high performance heat transfer units, consisting of a fan and its motor, a filter, one or two water coils (for cooling and heating) and a condensate drain pan. In this study horizontal concealed units were considered, installed in false ceilings, supplied with 100% fresh air through an AHU.

**Chilled beams (CB)** - Chilled beams can be divided into passive and active chilled beams (REHVA, 2006). The active chilled beams, which are the subject of this work, are induction units linked to 100% fresh air circuit by an AHU and to the hydraulic system by including coils of chilled and hot water. These units have no air filter or condensate drain pan, since its higher chilled water operating temperatures (when compared to conventional systems such as fan coil units), between 14ºC to 18ºC, avoids risk of condensation and hence the accumulation of particles on the coils.

Given the terminal units location and its air diffusion conditions, a ventilation efficiency of 100% for CB and 80% for FC is admitted.

**METHODOLOGY FOR POWER CALCULATION**

The method used for calculating cooling and heating power was the one in the Portuguese Decree-Law No. 118/98 (former RSECE), with some adaptations regarding the Portuguese Decree-Law No. 79/2006 (current RSECE) in order to meet the latest regulatory requirements. Some parameters were also introduced to estimate the actual operation of an HVAC installation, such as, the
heat recovery system efficiency or the temperature and moisture of the air blown by the AHU. Cooling power is determined from the balance of heat gains due to radiation through glass façade, heat conduction through the outer and inner envelope, internal heat gains due to metabolic activity of people, lighting and equipments, and heat gains due to the admission of outside air. Heating power is determined from the balance of heat losses through outer and inner envelope and by the admission of outside air.

This solution was adopted, rather than a detailed computer simulation, because it is intended to develop an expedite tool for predicting thermal power, allowing a simple way to compare two systems, so that, with this method is not intended to obtain precise values, but only a comparable order of magnitude, enabling the sizing of equipment for air conditioning systems at maximum load conditions.

**METHODOLOGY FOR ENERGY CONSUMPTION CALCULATION**

**Annual thermal needs**

The method used for calculating annual cooling and heating needs was the one adopted by Portuguese Decree-Law No. 40/90 (former RCCTE), with the introduction of some parameters from Portuguese Decree-Law No. 118/98 (former RSECE) and adaptations regarding the Portuguese Decree-Law No. 79/2006 (current RSECE), in order to meet the latest regulatory requirements. The main adjustments regarding the current RSECE, refer to the consideration of the annual profiles of occupancy, lighting and equipment in respect to healthcare facilities with inpatient units.

Some parameters were also introduced to estimate the actual operation of an HVAC installation, such as, the heat recovery system efficiency, the degree-days and also the introduction of the Humidity-Day original concept, that estimates, alongside and similarly to the Degree-Day, the dehumidification and humidification annual needs.

This solution was adopted, rather than a detailed computer simulation, because it is intended to develop an expedite tool for predicting energy consumption, allowing a simple way to compare two systems, so that, with this method is not intended to obtain precise values, but only a comparable order of magnitude.

**Degree-day and humidity-day**

To determine the annual thermal needs it is necessary to consider a set of climatic data representative of the region where the building is located, for which it was used the database of the Solterm software, settled by ADENE as a source of climate data for Portugal. Determination of the annual evolution of temperatures was based on the concept of Degree-Day, which considers for each hour of the day the sum of the differential temperature ($T_{\text{exterior}} - T_{\text{base}} > 0$) during the cooling period and the sum of the differential temperature ($T_{\text{exterior}} - T_{\text{base}} < 0$) during the heating period. Since this concept only allows to estimate the sensible thermal needs arising from the difference of temperatures, it became necessary to introduce a similar concept, Humidity-Day, that could estimate the latent thermal needs arising from the difference of absolute humidity - particularly because the case studies that are to be compared, namely CB, require humidity control.
**Electrical and gas consumption**

HVAC equipments electrical and gas consumption were calculated taking into account data provided by suppliers, namely, their efficiencies at different partial loads, such as chiller ESEER efficiency, boiler seasonal efficiency, AHU heat recovery system efficiency, fans and pumps efficiencies, among others.

**METHODOLOGY FOR CARBON EMISSIONS CALCULATION**

The methodology for calculating carbon emissions consisted in determining the carbon emissions from equipments that comprise the HVAC systems in the following stages:

1. Manufacture of equipments, including extraction of raw materials and processing;
2. Transport and distribution of equipment;
3. Energy consumed by the HVAC system during operation;
4. Maintenance activities, including manufacturing and transport of supplies;
5. Equipment and supplies end-of-life disposal.

The calculation methodology adopted in this work, in particular, the emission factors used, was based on the manuals provided by ADEME (2007a, 2007b), referring to the *Bilan Carbone* method, while still subject to some adjustments to the national context. The *Bilan Carbone* is a method for calculating GHG emissions, which uses readily available data to properly assess the direct and indirect emissions produced by a particular activity or territory. This method, developed by ADEME, is compatible with standard ISO 14064, the GHG Protocol initiative and the terms of the “permit” Directive No. 2003/87/EC on emissions trading system. In particular, it uses average emission factors and its uncertainty, so that calculated emissions allow to determine orders of magnitude, to carry out a comparative analysis of different solutions and to assess the main sources of emissions to proceed with its reduction.

**ANNUAL THERMAL NEEDS**

The annual thermal needs determined for FC system corresponds to 222.6 MWh / year for cooling (sensible and latent), 110.2 MWh / year for heating (sensible) and 3.7 MWh / year for humidification. Regarding CB system annual thermal needs it corresponds to 219.8 MWh / year for cooling (sensible and latent), 89.0 MWh / year for heating (sensible) and 3.0 MWh / year for humidification.

From the results shown in Figure 1, the following items should be emphasized:

- The differential temperature guaranteed by the AHU-CB in the cooling period ($T_{ins} = 15^\circ C$), is higher than the differential temperature by the AHU-FC ($T_{ins} = 22^\circ C$), which implies that the energy carried by primary air in the CB system is higher, which represents a decrease of the local thermal cooling (sensible) needs regarding the CB terminal units, corresponding to approximately 60% of the thermal needs of the FC terminal units. Overall, the sensible thermal cooling needs of the two systems are nearly identical, with relative difference of 4%;

- Since CB units are not able to remove latent load, so to avoid condensation in the air conditioned spaces, the AHU-CB must ensure additional dehumidification, contributing not
only to the fresh air latent load, but also to the internal latent load. Thus, the AHU-CB requires about two times more energy for dehumidification than the AHU-FC;
- During the heating period, it is seen that local thermal needs are not important, with a residual value of about 4% of the global needs, which may be a consequence of the net heat gain from solar radiation, but mainly due to net internal loads that are significant in areas with permanent occupation, as it is the case of an hospital inpatient ward;
- Regarding humidity, it can be seen that, despite the high power to be provided by the AHU humidifier, in terms of annual thermal needs it represents a negligible weight of about 4% of global thermal heating needs.

The difference between the global cooling thermal needs (sensible and latent) of the CB system and FC system is not significant, representing about 1%. The thermal heating needs are significantly lower in the FC system, with a relative difference of about 19% - since the fundamental weight lies in the AHU sensible thermal needs, it is not surprising that the relative difference between the two HVAC systems corresponds roughly to the difference between the fresh air flows, and the considered ventilation efficiencies.

**ELECTRICAL AND GAS CONSUMPTION**

The overall electrical power consumption determined for the FC system equipments corresponds to 156.2 MWh / year and to the CB system is 127.3 MWh / year. As for gas consumption it corresponds to 114.8 MWh / year for the FC system and to 92.7 MWh / year for the CB system. The following comments should be highlighted given the results obtained:
- In the overall balance, the annual thermal cooling needs, are approximately equal for both systems which represents identical electrical consumption for the chiller, with a relative difference of about 1%. Regarding the boiler gas consumption, the relative difference between the CB system over the FC system is about 19%, due to its annual heating needs;
- The choice of the CB system instead of FC system, helps reduce electricity consumption associated with the fans, by about 30%, since the absence of motors in the CB units.
contributes significantly to its decline. With regard to AHU fans, despite the fresh-air flow of the AHU-CB represents 80% of the fresh-air flow of the AHU-FC (due to the ventilation efficiency), electrical consumption associated with the fresh-air supply fan are approximately equal, which is mainly due to the additional pressure loss of about 125 Pa in CB units.

- The difference between the two systems pumps electricity consumption is small, about 1%;
- The humidifier of AHU-CB has a 20% reduction in electricity consumption compared to the AHU-FC, due to systems different air flows, a consequence of different ventilation efficiencies.

### PRIMARY ENERGY CONSUMPTION

Taking into account the electrical and gas equipment consumption, it can be converted to primary energy through the conversion factors set out in Portuguese Decree-Law No. 79/2006 (RSECE).
CARBON EMISSIONS

The calculation of carbon emissions of each HVAC system was carried out for a set of 106 terminal units, 4 circulation pumps and 1 AHU, over a period of 30 years. Estimated emissions in this period of time are of 879.0 ± 14% ton Ceq for the FC system and 707.0 ± 13% ton Ceq for the CB system. The results are grouped in the categories listed in Figure 4. Looking at the proportions of the analyzed categories, it is clear that the main weight for emissions lies in the energy consumed during operation, corresponding to the consumption of electricity and gas, affecting about 95% of global emissions in the balance of both systems during the given period. The materials used in the equipment manufacture has a relative weight of about 2% in both systems, equipment transport weights less than 1% and emissions from the systems maintenance activities have a weight more relevant in FC units (2.6%) than in CB units (1.4%), although also insignificant. Emissions associated with the disposal of materials at the end of life, either by the systems equipment or supplies used in maintenance activities, have a negligible weight, less than 0.1%. Figure 5 shows the distribution of average annual carbon emissions of the two systems, which allows to verify the following:

- The peaks of carbon emissions for both systems occur for years 1 and 16, when the installation of new HVAC equipment takes place, in particular, for the FC units and AHU (average lifetime of 15 years). In year 1 the contribution of emissions associated with equipment manufacturing and its transportation is more important in the CB system than in the year 16, because of its average lifetime of 30 years;
- In the years 11 and 21 also occur peaks in carbon emissions, although less significantly, associated with the replacement of pumps and their respective transport (average lifetime of 10 years);
- In general, CB system carbon emissions have less fluctuation during the period under consideration, which is due to less frequent maintenance operations responsible for emissions, and so it is verified that the most important contribution takes place in year 6, 11, 21 and 26, when AHU-CB motors and coils are replaced. Regarding the FC system, in addition to the indicated maintenance operations, additional operation of copper replacement associated with the rewinding of motors in every 3 years period, also contributes to emissions associated with maintenance operations.

![Figure 4 – Global carbon emissions in a 30 years period](image-url)
Carbon emissions were also determined from the *Bilan Produit 2008* software, developed by ADEME for estimating the environmental impacts of products. The relative difference between average carbon emissions calculated by the proposed methodology and the *Bilan Produit 2008* software correspond to 0.2% for the FC systems and 1.1% for the CB system, so it is within the range determined by the proposed method, since uncertainty corresponds to 14% and 13%, respectively.

COMPARISON OF CARBON EMISSIONS

The energy consumed during operation, such as electricity and gas, is the main source of emissions during the analyzed period of 30 years, of about 95% of global emissions. In order to highlight the main factors that can contribute to reducing emissions, some parameters were varied in the calculation tool to estimate energy consumption. The results obtained allow the following conclusions:

- The replacement of chillers with low ESEER efficiency, of 3.0, for high-efficiency chillers, with ESEER of 4.2 (base solution), lead to reductions in electricity consumption between 12% and 14% for FC system and CB system. As a result, the carbon emissions of the two systems are reduced by 8% and 10%;
- The base solution involves the use of a high efficiency boiler, 96%, which compared to a boiler with low efficiency, for example 80%, allows gas consumption reduction of 17% and emissions reduction of 5%;
- The AHU heat recovery efficiency presents itself as a key factor in the reduction of energy consumption, especially during the heating period, when the temperature differential is higher. It can be seen that the inclusion of a run-around-coil heat recovery module, with a sensible efficiency of 40% (base solution), allows a reduction of gas consumption by 36% and electricity by 2% in both systems, when compared with an AHU without heat recovery – this leads to emissions reduction of 14%. Considering the possibility of using a rotary heat exchanger system, with a sensible and latent efficiency of 75%, the reduction of emissions compared to the base solution is 16% and of 28% for an AHU without heat recovery module;
- It was observed that the decrease of 2°C indoor temperature at the heating period to 18°C might be significant, as it represents a reduction of gas consumption by 27% and thus emissions reduction by 7% and 8%, for the FC system and CB system, respectively. Due to
calculation methodology limitations regarding the annual thermal needs, it is not possible to accurately perform this analysis for the cooling period, as it would require an a detailed computer simulation;

- Air distribution and diffusion by terminal units can be critical for the decrease or increase in thermal loads regarding fresh air from the AHU, due to the effect that the ventilation efficiency has on it. Since there is no clear definition for the ventilation efficiency for each system configuration, it was intended to determine how its variation can influence the carbon emissions. Assuming that the FC system has a 80% ventilation efficiency (which seems reasonable), it was observed, from CB solutions of ventilation efficiency between 90% and 100%, a reduction in the electricity consumption of 8% and of 10% in gas consumption, and consequently 8% reduction of emissions.

![Figure 6 – Variation of emissions according to the chiller ESEER efficiency and to the boiler efficiency](image1)

![Figure 7 – Variation of emissions according to the heat recovery efficiency and to the ventilation efficiency](image2)

**COMMENTS AND CONCLUSIONS**

There is a growing concern in the international scene for reducing carbon emissions associated with buildings systems and facilities life cycle, including HVAC systems, as evidenced by several scientific articles published in this sense (Prek, 2004; Wong, 2010 and Dec, 2011). This project introduces in Portugal the carbon emissions theme applied to HVAC systems, thereby filling a void in national studies of this kind.
Using the proposed methodologies for estimating energy consumption and carbon emissions, the main results are listed below:

**Final energy consumption** - CB system operation provides an annual reduction in electricity consumption by 18.5% and 19.3% in gas consumption, when compared to the FC system.

**Primary energy consumption** - CB system operation provides an annual reduction of 18.6% in primary energy consumption, compared to the FC system, featuring per terminal unit, 520 kgoe/un in the FC system and 423 kgoe/un in the CB system. FC system primary energy consumption can be broken down into 31% for cooling, 21% for heating and humidification, and 48% for ventilation, as for the CB system it represents 38% for cooling, 22% for heating and humidifying and 40% for ventilation, so the absence of motors in the CB units helps to reduce the contribution of ventilation.

**Carbon Emissions** - In the analyzed period of 30 years, the reduction of carbon emissions is about 20%, when opting for replacement of the FC system by the CB system, featuring per terminal unit, 8.3 ± 14% tonC\textsubscript{eq}/un in the FC system and 6.7 ± 13% tonC\textsubscript{eq}/un in the CB system. Looking at the proportions of the analyzed categories, it is clear that the main weight for emissions lies in the energy consumed during operation, corresponding to the consumption of electricity and gas, affecting about 95% of global emissions in the balance of both systems during the given period. Thus, to reduce carbon emissions of such systems, it is important to select equipment with high energy efficiencies, with heat recovery modules, free-cooling ability and in terms of operation, acting on the equipments operating parameters, namely, change, within the limits of comfort, indoor temperature and humidity. Since the case studies are set in an hospital context, particular focus should be paid to the modification of indoor temperature and humidity, since patients weakened state requires specific comfort conditions (ASHRAE, 2003 and ACSS, 2010).

It is concluded that the CB system has higher energy performance and consequently also better results in terms of carbon emissions, given the major contribution of energy consumption in global emissions. Thus, it should be emphasized the importance of developing expedite tools to estimate the annual thermal needs and equipment’s electricity and gas energy consumption. It is also worth noting the introduction of the Humidity-Day original concept, that estimates, alongside and similarly to the Degree-Day, the dehumidification and humidification annual needs, which the calculation methods adopted in the Regulations (RCCTE) do not account for, largely due to its weight in global thermal balance, which is considered to be negligible. However, it can be seen, that despite the negligible weight of humidification needs during the heating period (about 3% of annual heating needs), dehumidification during the cooling period represents a considerable weight of about 20% of the annual cooling needs.

One important issue, which may be subject of future studies, relates to the economic savings associated with energy bills, both in terms of electricity and gas, which would allow a broader comparative analysis. In future studies it also would be interesting to apply and validate the developed calculation tools for other systems, as well as deepening the concept of humidity-Day and try to assess its relative error regarding functioning buildings with real energy consumption.
REFERENCES


Web-sites:

ACSS. Web-site of Administração Central do Sistema de Saúde: www.acss.min-saude.pt/
ADENE. Web-site of Agência para a Energia: http://www.adene.pt/
Carbon Trust. Web-site of Carbon Trust: http://www.carbontrust.co.uk/
DGEG. Web-site of Direcção Geral de Energia e Geologia: http://www.dgge.pt/
IPCC. Web-site of Intergovernmental Panel on Climate Change: http://www.ipcc.ch/