Integrated Energy Modelling to Support District Cooling Optimisation: Methodological Approach

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Abstract

In a district cooling system different kinds of cooling production can be combined (e.g., vapour compression chillers, absorption chillers, and free cooling). Controlling those systems in an efficient way is a complex problem: the cooling demand is much more difficult to predict than the heat demand and, as for absorption chillers, heat sources such as the solar energy and the waste heat are not predetermined by the designers.

The EU project INDIGO deals with the improvement of District Cooling (DC) systems. Its main goal is the development of a more efficient, intelligent, and cheaper generation of DC systems. The results of INDIGO will include the development of:

predictive controllers;

system management algorithms;

an open-source planning tool.

To validate the results, the consortium is analysing some case studies. The proposed solutions for DC systems will be installed in the Basurto Hospital campus in Bilbao. Different parts of models that regard the buildings and all the relevant components of the DC system are being developed:

1. generation systems;
2. distribution and storage systems;
3. HVAC systems;
4. thermal behaviour of the buildings, considering also internal loads and building use.

The first three parts are being simulated by means of Modelica, an open-source object-oriented modeling language that provides dynamic simulation models for building energy and control systems. The fourth part is being modelled with EnergyPlus. They are going to be integrated through the Functional Mock-up Interface (FMI) for co-simulation.

The models of some building envelope elements are being validated considering experimental measurements (heat flow rates, temperatures, entering solar radiation).

Component models for the air handlers and for the fan-coils found in the studied buildings are developed in Modelica. Different kinds of chillers are modelled. Particular attention is paid to the distribution system, where thermal and hydraulic effects must be considered jointly.

All the developed models will be validated, both independently and considering the integration, using data acquired at the test-site.

The validated models will be considered a reference point for the development of the innovative controllers, of the management strategy, and of the planning tool. The new models developed in Modelica will be part of a District cooling open-source library (DCOL).

1. Introduction

This paper presents the role of the energy models in the development of INDIGO, a research project that is funded by the European Union in the context of the Horizon 2020 research and innovation program. The project started in March 2016 and will end in August 2019. Its main goal is the improvement of the district cooling (DC) systems.

In comparison with the heating systems, the cooling systems present problematic aspects related to the greater difficulty in the prediction of the energy

demand. The reason is that the energy demand can change quickly because it is influenced by factors such as the solar radiation and the internal heat loads.

Another problematic issue is that the difference between the supply water temperature and the return water temperature for DC loops is generally around 8 °C, while in district heating loops the difference is usually greater than 40 °C. That causes an increase in the cost of the piping system and of the energy requested for pumping.

The improvement of the DC systems shall be achieved through the development of new tools for the design and for the management of district cooling systems:

- predictive controllers that will be responsible for determining the setpoints of the mechanical systems (some of them will include self-learning algorithms), at all levels (generation, distribution, storage, AHUs, and fan-coil units). They will develop on the basis of "reduced" and validated versions of the energy models;
- an innovative management strategy, on which the controllers will be based, will consider energetic aspects, environmental aspects, and economical aspects;
- an open-source planning tool for the evaluation of existing systems and for the design of new district cooling systems. It will be based also on the results of simulations;
- an open library including physical/mathematical models developed in Modelica of the components that compose a DC system that will be called *District cooling open-source library* (DCOL).

The models regard mainly the real situation of the Basurto Hospital, in Bilbao, which is divided in 20 buildings, among them 9 are mechanically cooled. The results of INDIGO will be applied and measured in the plants relative to that facility. The DC system was installed in 2003 and extended in 2011 by Veolia-Giroa. The chilled water is produced by two absorption chillers and by four vapour compression chillers. The system supplies chilled water always at 7 °C (as setpoint temperature) and it modulates the water flow rate. The absorption chillers are cooled by water loops, one vapour compression chiller is water-cooled while the other three electric chillers are air-cooled (Fig. 1). The hot water, which is used by the absorption chillers and to heat the buildings, is heated by the waste heat of a cogeneration system. That heat can be stored in a water tank. The cogeneration system is activated on the basis of the economic convenience of producing electricity.

In this case the cooling demand is particularly variable because it depends on the number of scheduled surgeries and on the occupancy level as well.

The internal zones are conditioned mainly though Air Handling Units (AHUs) or through fan-coil units. Since the local regulations for hospitals do not permit air recirculation, an important amount of energy is requested for the treatment of the outdoor air.

In the other two pilot cases, located in Barcelona, the models and the INDIGO solutions (controllers and management system) will be tested without a physical installation. They are not considered in this paper.

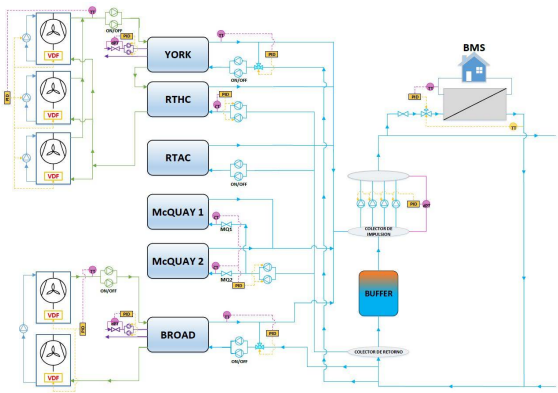

Fig. 1 – Scheme reporting the situation of the cooling production/distribution plant in the hospital (INDIGO project, 2016)

2. The Integrated Model

2.1 FMI

Different partners of the project consortium are developing different parts of models that regard the buildings and the DC system of the Basurto hospital. The different parts will be integrated and they are:

1. generation systems;
2. distribution and storage systems;
3. HVAC systems inside the buildings;

4. building geometry, thermal behaviour of the building structures, internal loads, and building use.

The fourth part will be developed in EnergyPlus and will be converted into functional mock-up units (Blochwitz et al., 2012; Nouidui et al., 2014) that will be then imported and used in a Modelica model that includes the AHUs. The weather data will be integrated in the same functional mock-up unit (FMU) of the building. The FMU will have as input variables latent and sensible heat gains provided by the AHUs to each conditioned thermal zone and as output variable room conditions (zone air temperature and relative humidity) and outdoor air conditions.

The combined Modelica-AHUs with EnergyPlus-FMUs will be then converted into another FMU and used for training an advanced control algorithm to be developed in INDIGO and for the integration with the distribution-storage-generation models, which are being created in Modelica.

The integration of different tools allows the exploitation of their different capabilities. EnergyPlus is a whole building energy simulation software, the development of which is funded by the U.S. Department of Energy – Building Technologies Office. It is free, open-source, and cross-platform. In EnergyPlus many physical-mathematical models relative to the building physics (as well as to the HVAC systems) are already available and validated. Modelica is a non-proprietary, object-oriented, equation based language. The use of a Modelica library (Wetter et al., 2014) and the development of new models require the use of a Modelica simulation environment (some environments are commercial, a few environments are free). The use of Modelica allows for a greater flexibility than EnergyPlus.

2.2 Validation

The models will be validated, at different levels, using measured data. The quality of the measured data will be checked in order to eliminate the unreliable ones. The validation process will consider statistical test methods, with the definition of an acceptable range of accuracy with respect to the model goal. It will be an iterative process.

The validated models will be then used as a tool for the improvement of the plant and for the development of other tools, such as the controller, the management strategy, and the planning tool.

A monitoring campaign has started in summer 2016 and is going to be completed in summer 2017. A Building Management System (BMS) is installed and some data used for the validation were already being measured, while other data are being measured or are going to be measured because it was requested by the measurement plan developed for this project.

2.3 Generation Systems

The models of the generation system that are being developed are: water cooled vapour compression chillers, air cooled vapor compression chillers, absorption chillers, cooling towers, heat exchangers (plates and shell & tube), and pumps. The development is being carried out in Modelica. The following measurements, with a time step equal to 1 minute, are available:

- cooling energy produced by each chiller (elaboration from water flow rate and temperatures);
- total cooling energy produced by the plant (elaboration from water flow rate and temperatures);
- electric consumption in each chiller;
- gas consumption of the cogeneration engines;
- supply and return temperature of the hot water loop for each absorption chiller;
- supply and return temperature of the heat rejection loops (cooling towers);
- water temperature in the supply and return manifolds;
- outdoor temperature.

2.4 Distribution and Storage Systems

Outside the building where the generation system is located, there is a buffer tank for cold water that is installed between the return and supply manifolds (its volume is 25 m^3). The chilled water temperature is measured at the top and at the bottom of the tank. The length of the distribution piping is about 2 km (supply pipes plus return pipes), split in two branches. The DC grid sends chilled water to 9 buildings where substations are installed. The total

substations are 11 because in two of the buildings there are two substations. Only in a substation there is a heat exchanger, while in other ones there are hydraulic separators between the DC loop and the loop inside the buildings. In some cases, energy meters are installed in the building side of the substation.

The central pumps are connected to a frequency converter that allows the variation of their speed.

As for the models of valves, pumps and fittings, the relative models available in the Modelica Standard Library are being used. As for the pipes, a new model, based on the "plug-flow" approach, is being developed. The roughness of the pipes, since it influences the hydraulic resistance and it raises the water temperature, the heat losses through the pipes, and the thermal inertia of the distribution system are being considered.

As for the water tanks, phenomena like the thermal energy charging and discharging process, the stratification, and the heat losses are being considered.

2.5 HVAC Systems

Several libraries exist in Modelica for modelling and simulation of HVAC systems. The INDIGO team decided to use the Annex60 (Wetter et al., 2015) Modelica library as a basis for the component models and develop whichever component was not included in the library.

This section deals with the modelling and simulation of the Air Handling Units (AHUs) that serve one of the demonstrator buildings, the Aztarain Block in Basurto Hospital. Aztarain is served by two main AHUs as the one shown in Fig. 2.

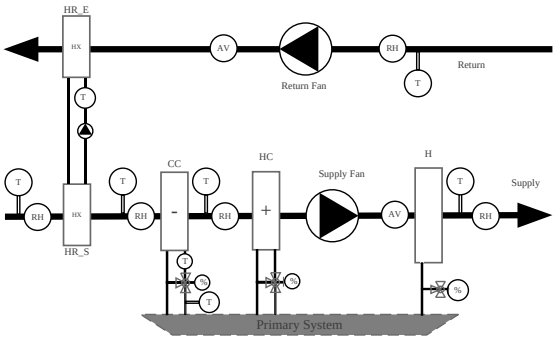

Fig. 2 – Schematic of Aztarain AHUs (Sterling, 2016)

The unit is composed of:

- heat recovery (HR) based on two heat exchangers with a close water circuit as transfer fluid;
- cooling coil (CC);
- heating coil (HC);
- supply and return fans;
- humidifier (H);
- sensors: temperature (T), relative humidity (RH), air velocity (AV), valve position (%).

In the Aztarain building an AHU serves pressure positive rooms for immuno-depressed or critical patients. Another AHU serves all the other areas. For the underground floor the supplied air can be post-heated or post-cooled by water coils installed in local boxes, where the renovation airflow rate is mixed with recirculated air.

The Annex60 library contains models for the fans, the heating coil, and the humidifier. However, a model for the cooling coil is not implemented yet. An initial implementation of the cooling coil model has been made based on the efficiency-NTU method.

These models will be validated using real operation data from the facility after the monitoring and instrumentation is upgraded to match the instrumentation shown in Fig. 2. Attention will be focused on the cooling coil given the aim of the INDIGO project to improve operations of district cooling systems.

To calibrate and validate the cooling coil models a procedure based on (Febres et al., 2015) has been proposed whereby the full range of operation of the coil is explored at discrete steps. This is done by modulating the cold-water control valve as shown in Fig. 3.

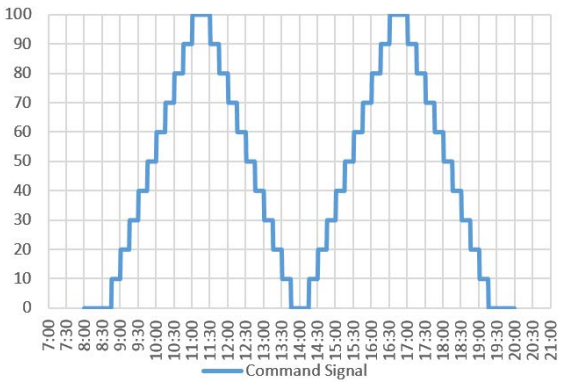

Fig. 3 – Controlling variable signal (Sterling, 2016)

In this validation scenario, the input and output air temperature and relative humidity are monitored at 1-minute intervals over the validation period. With this approach, it is possible to characterise the relationship between valve command and output conditions and hence validate the suitability of the model for the specific coil.
The rest of the components will be validated during normal operations to avoid disrupting the hospital functioning.

2.6 Building, Internal Loads, Users

Some measurements relative to the building have started in summer 2016. They regard the building envelope.
The thermographic camera has been used for detecting irregularities in the building envelope. In this way, the best position for the heat flow meter can be evaluated. The heat flow meter was used to measure the heat flow rate through the roof and the external walls of the Aztarain building. During the same period the outdoor and the indoor air temperature, the outdoor and the indoor surface temperature were measured (Fig.s 4 and 5). The data relative to the solar radiation and to the wind velocity and direction are available through the weather station C039 - Deusto of the Basque agency of meteorology Agencia vasca de meteorología. A new solar radiation sensor will be installed in the next months. Generally, the measurements made through the heat flow meter are indicative when there is an important difference (at least 10 °C) for some consecutive days between the indoor temperature and the outdoor temperature. Normally this happens during the winter season. Nevertheless, in this case the measurements were carried out in summer because the research is interested in modelling the cooling demand and therefore in analysing the behaviour of the structures in hot conditions and when they are stricken by a high solar radiation.

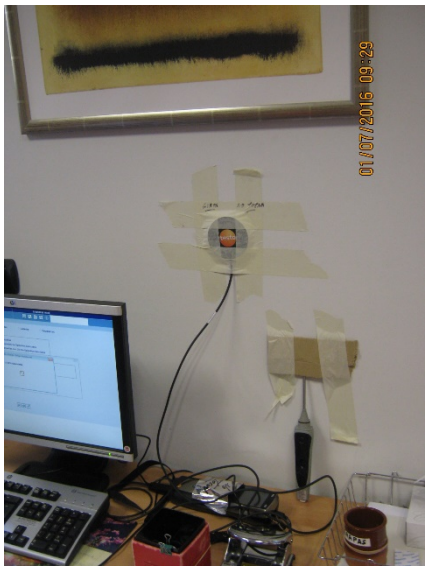

Fig. 4 – Internal measurement equipment for heat flow rate, surface temperature, and air temperature (Passerini, 2016)

The validation of the models of the walls and of the roof is considering: amplitude of peak, time between two peaks, minimum, maximum and mean values, slope and the number of inflection points, attenuation factor relative to the external and the internal oscillations, time delay between external surface temperature and internal surface temperature or internal heat flow rate. The surface emissivity is being evaluated through a thermographic camera: the surface temperature is measured at the same time with a thermographic camera and with a surface thermometer and the emissivity considered by the thermographic camera is adjusted until it measures the same value measured by the surface thermometer.
The surface solar absorptance considered in the model is adjusted in order to have an acceptable agreement between measured and calculated outside surface temperatures. The results obtained with different models of the outdoor convection coefficient are going to be compared with measured data in order to select the most appropriate one for the analysed case.

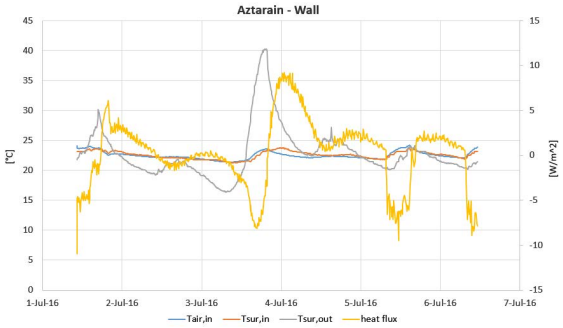

Fig. 5 – Elaboration of measured data relative to an external wall of Aztarain building (Passerini, 2016)

A pyranometer was used with different sky conditions in order to evaluate the ratio between the solar radiation flux density (W/m²) entering the windows and the external solar radiation on a plane parallel to the window.

Additional measurements to be carried out in order to improve the input accuracy regarding mainly the internal loads and the behaviour of the users are:

- internal heat gains (metering of the consumption of medical equipment, communication racks, UPS systems, IT equipment, and any other relevant equipment);
- window openings (magnetic sensors);
- CO_2 concentration.

The correlation between the opening of the windows and other parameters (e.g., CO_2 concentration, indoor and outdoor temperatures) will be investigated.

Since the control of the HVAC system is based on the return air temperature, the rooms have been divided in thermal zones by gathering all the rooms of a floor that are supplied by the same AHU. For the underground floor of the Aztarain building the division has considered also the distribution of the rehaeating/recooling boxes.

3. Conclusions

In the INDIGO project an important role is played by the creation of dynamic models of a DC system and of the connected cooling demand.

The geometry of the buildings and the thermal properties of the structures, as well as some AHUs, the water buffer tank, some chillers, and other components have been modelled. The integration of the building model with the AHUs models was tested.

In the next weeks, the parameters will be adjusted and validated on the basis of the data monitored in summer 2016. The validation will be completed after the elaboration of the data that will be measured in the next months and in summer 2017.

Through the validated models, improvements of the technical plants and of their management will be tested. Some proposed improvements will regard the control logics, while other improvements will regard the installation (e.g., the installation of a new solar thermal system that can feed the absorption chillers).

The models will be useful in evaluating whether there are discrepancies between the expected performance and the real performance, in finding the causes of the possible discrepancies and in quantifying the energy and economic savings in comparison with the previous situation (before the implementation of INDIGO solutions).

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Nomenclature

Symbols

DC	District cooling
FMI	Functional mockup interface
FMU	Functional mockup unit

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