TESTING AND VALIDATION OF SIMULATION TOOLS OF HVAC MECHANICAL EQUIPMENT INCLUDING THEIR CONTROL STRATEGIES. PART II: VALIDATION OF COOLING AND HEATING COIL MODELS

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ABSTRACT

This paper presents detailed information about testing and validation of cooling and heating coil models. The work has been carried out under Subtask D of the International Energy Agency's SHC Task 34/ECBCS Annex 43 (Testing and Validation of Building Energy Simulation Tools). The goal of this Subtask (Mechanical Equipment and Control Strategies) was to develop and test methods that would help evaluating, diagnosing and correcting HVAC mechanical equipment simulation software.

INTRODUCTION

As a basis for all studies in the context of this project cooling and heating coils have been used that have been installed in an air conditioning system serving several test rooms in a laboratory building.

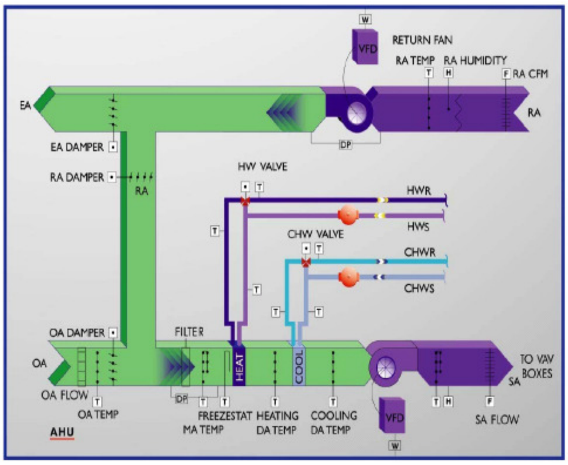

Figure 1 Schematic plot of AHU system with measuring points

The laboratory building is located in Ankeny, Iowa, U.S. The air-conditioning system as well as the two hydronic systems (heating and cooling) supplying the coils is equipped with many sensors that allow collecting minute-by-minute data of all relevant parameters. Finally, three sets of data have been collected: one for the heating coil and two for the cooling coil covering a total time period of 30 days. Data has been collected in 2005 and 2006. Due to maintenance services at the HVAC system operating conditions of the system have been slightly changed which has to be taken into account for the model validation. These modifications are for instance in terms of physical properties of chilled water and calibration of sensors. Figure 2 shows the concentration profile of Propylen-Glycol percentage of chilled water and periods of chilled water tests I and II.

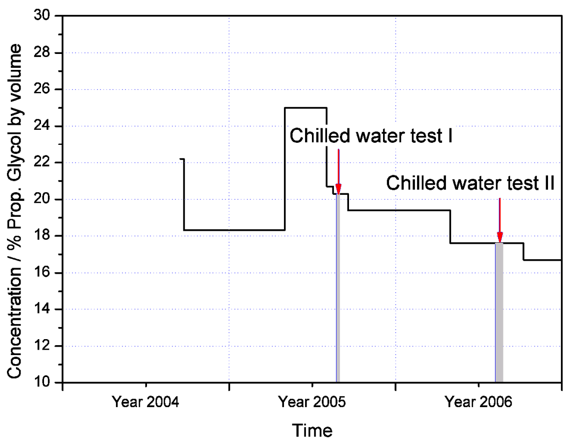

Figure 2 Historical to current ERS Chilled Water System Concentration

METHODOLOGY

The procedure of developing validation test methods was the same for both heating and cooling coil:

In a first step information from the manufacture submittal has been assorted and pre-processed allowing a user to generally set up and configure a coil model. The information is related to geometry and materials the coils consist of as well as nominal coil performances. Doing it this way basic input and parameter requirements of different types of simulation programs could be satisfied.

In a second step quasi-steady state performance data derived from the data collected on-site during the experiments have been used to further characterize coil performance at different part load conditions.

Both data coming from the manufacturer as well as data derived from measurements can be used for model calibration. The following section will give some more insight into the type of data available.

Cooling coil

Table 1 shows performance data of the cooling coil as available from the manufacturer submittal.

Table 1

Cooling coil data from Manufacturer submittal

Cooling Coil Performance – Manufacturer data	
Entering Air Temperature	27.8°C db 19.2°C wb
Leaving Air Temperature	12.5°C db 12.2°C wb
Leaving Air Density	1.23kg/m³
Air Pressure Drop	0.194kPa
Entering Liquid Temp.	6.7°C
Leaving Liquid Temp.	12.1°C
Liquid Flow	1.8l/s
Liquid Pressure Drop	22.4kPa
Total Cooling Capacity	35.8kW

Based on the data presented before some additional information required to fully describe nominal performance of the coil have been calculated using both general psychometric equations and some ARI definitions used to assess coil performance under rated boundary conditions. Table 2 represents these additional data estimated based on manufacturer submittal describing cooling coil performance.

Table 2

Cooling coil data estimated from Manufacturer data

Cooling Coil Performance – estimated data	
Barometric pressure	101.3 kPa
Entering Air Relative Humidity	44.4%
Entering Air Moisture	0.0104 kg/kg
Leaving Air Relative Humidity	96.9%
Leaving Air Moisture	0.0087kg/kg
Air Flow Rate at leaving air conditions	5430m³/h
Latent Cooling Capacity	7.3kW

Unfortunately nominal coil performance provide by the manufacturer does not allow to satisfactory calibrate coil models because part load information was missing. Therefore - as mentioned before - additional performance data has been extracted from quasi-steady state operational points that would help the modeller to parameterize the coil models. It has been taken care that performance data of the cooling coil covered both cooling coil in dry and wet regime. Due to laboratory conditions cooling coil entering air conditions have been artificially modified to scanning a wide range of coil performance: hot wet, hot dry, cool wet, cool dry, and 100% outside air that delivers some more stochastic input data. Finally 14 additional test points have been provided to the modellers. These test point are in a range of 23...67% of total nominal cooling capacity at very different temperature and humidity conditions than nominal rated. Quasi steady state experimental data has been checked to fulfil energy and mass balances which has required some kind of measuring error compensation because raw experimental data itself did not completely fulfil energy and mass balances at the coil. Figure 2 and Figure 3 exemplary show data compensation adapted to the experimental data. Mostly there was a constant offset regarding both water side temperatures and coil leaving air temperature of about 0.1..0.2 K whereas coil entering air temperatures had to be corrected by up to 1K depending on temperature. Relative humidity was corrected by 1..2%. Measurement error compensation was difficult at saturated leaving air conditions when leaving air humidity was reported to be 95% and higher.

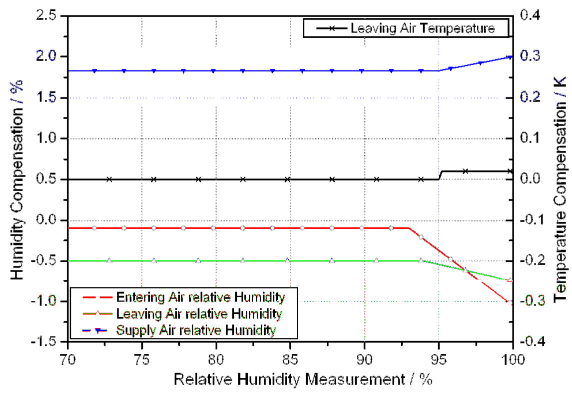

Figure 2 Cooling coil with variable water flow rate

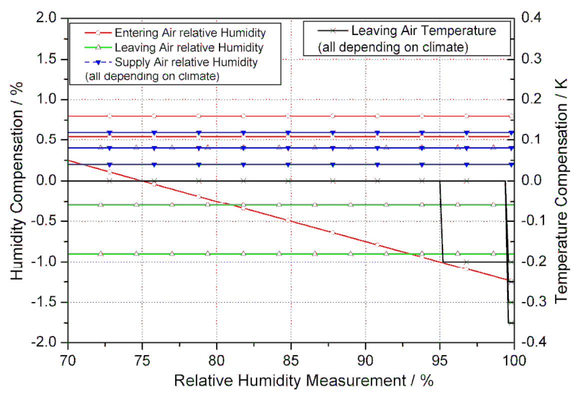

Figure 3 Cooling coil with variable water flow rate

In terms of empirical model validation the predictions of the simulation models fed with input data only have been compared with experimental data only but not directly against each other.

Heating coil

Similar to the cooling coil Table 3 shows performance data of the heating coil as available from the manufacturer submittal

Table 3
Heating coil data from Manufacturer submittal

Heating Coil Performance	
Entering Air Temperature	4.44°C db
Leaving Air Temperature	37.78°C
Air Pressure Drop	0.0498kPa
Entering Liquid Temp.	82.28°C
Leaving Liquid Temp.	71.06°C
Liquid Flow	1.33l/s
Liquid Pressure Drop	3.67kPa
Total Heating Capacity	61kW

Based on the data presented before some additional information required to fully describe nominal performance of the heating coil have been calculated using both general psychometric equations and some ARI definitions used to assess coil performance under rated boundary conditions. Table 4 represents these additional data estimated based on manufacturer submittal describing cooling coil performance.

Table 4
Heating coil data estimated from Manufacturer data

Heating Coil Performance	
Barometric pressure	101.3kPa
Entering Air Relative Humidity	50%
Entering Air Moisture	0.00259kg/kg
Entering Air Density	1.27kg/m³
Leaving Air Moisture	0.0026kg/kg
Leaving Air Density	1.13kg/m³
Air Flow Rate at coil leaving air conditions	5780m³/h

Also heating coil performance has been additionally described using quasi-steady state conditions derived from experimental data. Since the heating coil performance does not necessarily need to account for humidity conditions and therefore operating conditions have not that complexity as for the cooling coil only two additional sets of coil performance data have been derived from experimental data and provided to the user of the validation test procedures. Part load heating capacity represented by those additional steady state conditions is 20 and 72% of nominal rated heating capacity and therefore allows calibration of heating coil model for a wide range of part load operation.

TEST LOGIC

Additional comparative model validation test procedures have been developed for cooling and heating coil that account for a wider range of input data variation than having been realized under experimental conditions. Here predictions of the coil models have been compared against each other. Comparative model validation covers biannual time periods: heating season for the heating coil and cooling season for the cooling coil.

There have been two different set of test created for both cooling and heating coil validation purposes:

- Comparative test
- Empirical test

The tests should be run step-by-step beginning with the comparative test. The idea behind this consecutive process is to start with a simulation model that has been calibrated based on some general information about coil performance that was available from the manufacturer submittal and to end with a model calibrated based on detailed experimental data collected from coil operation in a real plant.

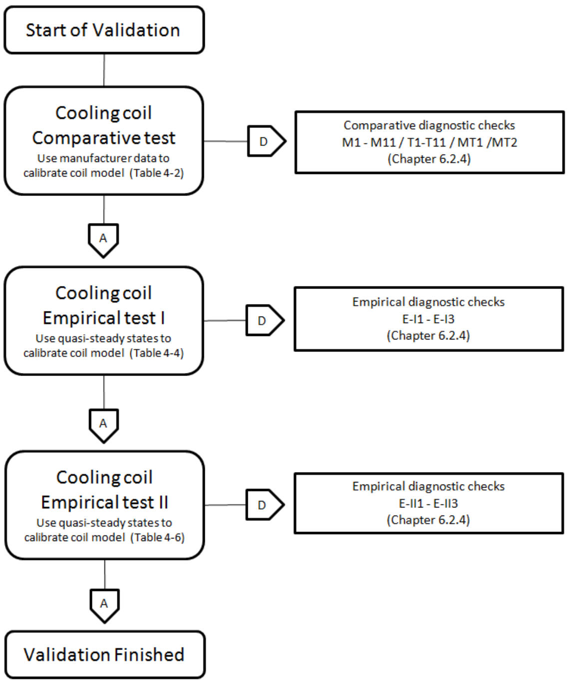

Figure 4 Cooling coil overall test logic (Abbreviations: A=Agree; D=Disagree)

Figure 4 showing the cooling coil test logic helps to clarify how to pass through the several validation test. From the manufacturer submittal only one single point of coil performance was known (see Table 1-4) that roughly represents a full load coil performance. No more information about part load performance is available for running the comparative tests. Thus the modeller has to run the comparative tests with their own standard model part load approach that can considerably differ between models. The additional calibration points provided to the modeller when running the empirical tests should allow calibrating the model with respect to both part load performance as well as real installation and operating conditions (i.e. physical properties of the chilled water) that differ from the performance conditions found in the manufacturer submittal.

Comparative testing

Comparative validation takes different types of coil control into account: either mass flow or temperature controlled coil. Figure 5 and Figure 6 show different configurations as used for the comparative validation. The real world HVAC system accounts for variable mass flow only but in principle the same model as set up for comparative testing could be used for empirical validation after re-calibration based on additional steady-state performance data.

Comparative validation of coil models has to be done mostly based on artificial boundary conditions. The coil entering air temperature and humidity conditions have been taken from a TMY weather data set that represents local conditions. Air flow is either constant (CAV) or variable (VAV) where VAV has to be modelled as a daily profile that repeats periodically. Figure 7 exemplary shows the air volume profile for the cooling coil comparative testing.

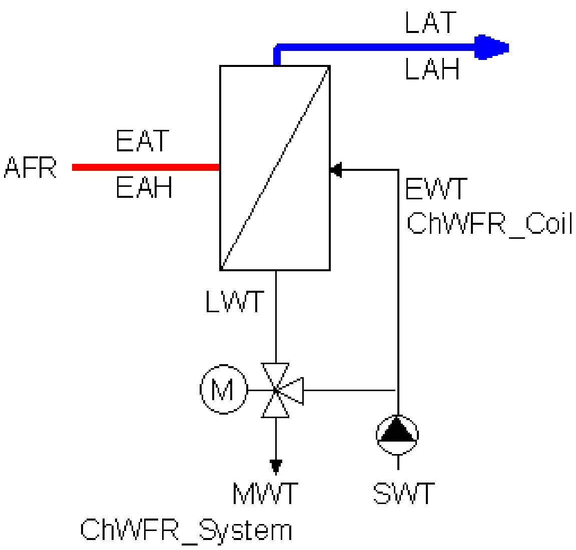

Figure 5 Coil with variable water flow rate

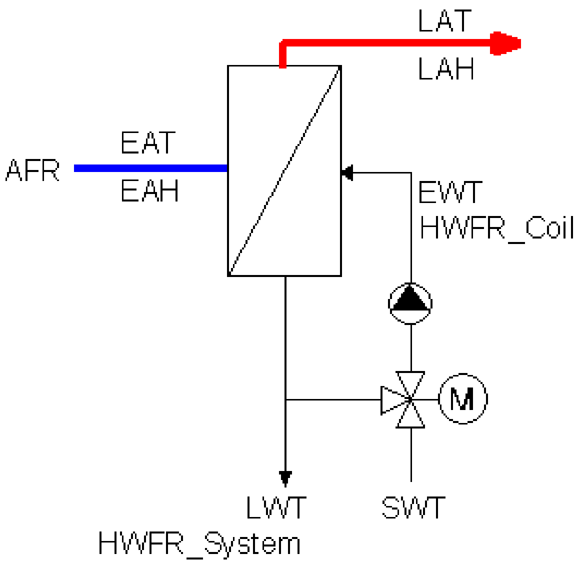

Figure 6 Coil with constant water flow rate

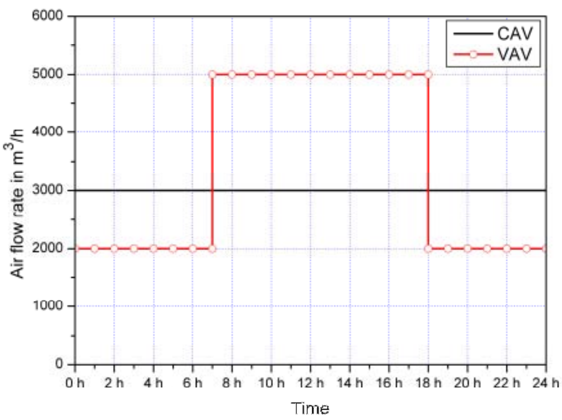

Figure 7 Air flow rate daily profile for cooling coil comparative testing

Beside load control and air flow rate also set point temperature of coil leaving air and in case of the cooling coil physical properties of the waterside fluid have been varied. Finally, there are 16 comparative test cases for the cooling coil and 8 comparative test cases for the heating coil validation available. Results of five different simulation programs participated developing the tests are available. Depending on boundary conditions (i.e. type of control) some of the programs have not been able to run all simulations.

MODELLING APPROACHES

There have been five different simulation programmes participating in developing validation test procedures. From those programmes one programme only was based on a pure geometric description of the coil appliance whereas all other tools were using more or less the same way of modelling using characteristic curves. These characteristic curves characterize two effects described as follows:

1. Impact of water and air side flow rates on the overall UA-value of the coil
   Generally programs do use correlations as

   $$UA=UA_{nom}*(Flow/Flow_{nom})^x$$

   to describe dependencies between UA value and flow rates. The value x differs among programs but is about 0.4...0.6 for the air side and 0.7...0.8 for the water side of the coil.

2. In case of cooling coil impact of entering air humidity on fraction of latent coil load. Figure 8 shows an example of a typical performance curve as used by most of the programs to decide whether coil operates in dry (i.e. no latent load) or wet (i.e. sensible load<total coil load) regime.

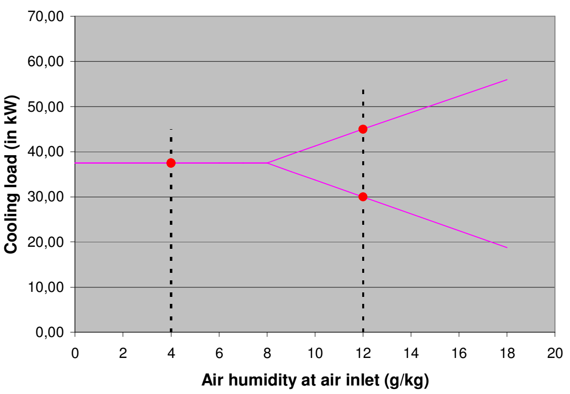

Figure 8 Cooling power (sensible and latent = total) for 2 points (1 in dry regime and 1 point in wet regime)

In the geometric approach the coil was modelled by splitting it into several sub-elements as exemplary depicted in Figure 9. For each of the sub-elements the full set of detailed heat and mass transfer balances have been taken into account.

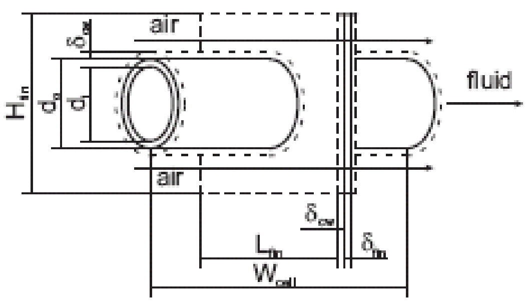

Figure 9 Sketch of a modelled cell as a part of a finned coil

Other models using characteristic curves to predict coil performance are based on the general approach that estimates heat transfer from water to air side of the coil in dependency on a given reference point and air and water flow rates during part load. The specific heat transfer capacity of the coil (UA-value) therefore is normally divided into 3 parts (water - coil construction, internal of the coil construction, coil construction – air). The heat transfer rates at the water and at the air side depend on flow rates. The final report of this IEA project (Felsmann et al. 2008) summarizes different calculation approaches simulation models are based on.

RESULTS

A lot of results have been produced by the simulations programs.

Cooling coil

Figure 10 exemplary shows the total cooling load during July 31 as predicted by the simulation programs. It is a hot and humid day with a cooling load appropriate to the nominal load. The comparison of load profiles shown in the graphic offers big differences between programs.

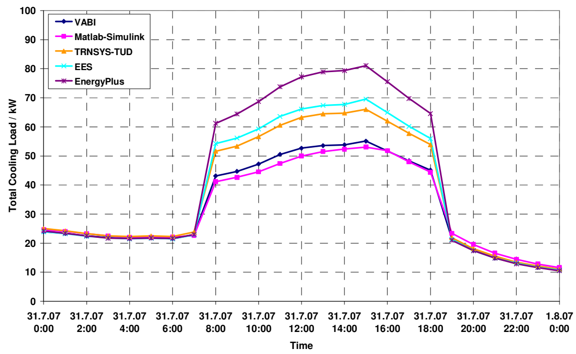

Figure 10 Total Cooling Load on July 31 (hot humid)

Heating coil

Figure 11 exemplary shows the results of the sensitivity study analysing dependency of mean leaving water temperature on leaving air temperature set point.

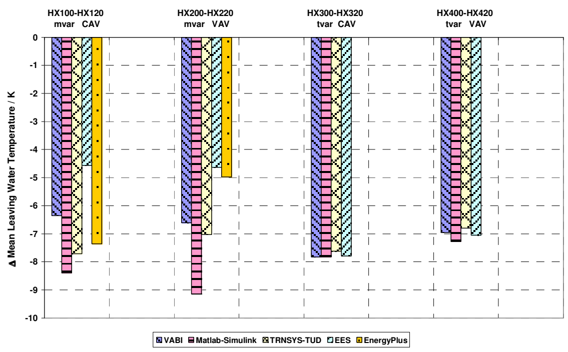

Figure 11 Sensitivity of mean leaving water temperature against leaving air temperature set point

The final report (Felsmann et al 2008) contains a full set of results and detailed description and information on validation procedures. The modellers have been provided reports describing their experiences how to model cooling and heating coils and how to run the tests developed under IEA Task34/Annex 43.

CONCLUSION

Coil models seem to be very common. A lot of different coil models are available either commercial or public. They are quite easily to use and easily to calibrate. It is difficult or not possible to predict part load performance of heating and cooling coils when only nominal performance data are known. Results provided by different simulations programs under identical boundary conditions may differ a lot depending on mathematical approach that is used.

Test procedures have been developed to validate both heating and cooling coil models under a wide range of part load using either comparative or empirical methods.

Experiences gained during the project are:

- Different simulation models used by different participants ask for different information to set up the models. Some of this information is hardly to get because knowledge about configuration and/or performance of components are either too detailed (from the manufacturer's point of view) or not well documented (in an existing system).
- Data submitted from the manufacturer including performance curves can not be directly assigned to an existing system. Performance data under laboratory conditions may differ from those under real world conditions. For that reason new sets of calibration point have been extracted from the experimental data.
- There is a different understanding among people on which information should be provided to the modeller for validation purposes. Normally only data available from the manufacturer submittal can be used for the parameterization of simulation model. For this empirical validation work, experimental data was used to calibrate simulation inputs (set up the models). Such data have been provided to the modellers otherwise there is no chance to consider for the differences between laboratory (manufacturer data are based on) and real world conditions (experimental data used for validation are based on).
- It was found from both heating and cooling coil tests that models with a heat transfer coefficient UA that is independent from the coil flow rates are not able to predict coil performance correctly when either flow rates are changing (i.e. when the air flow rate is variable or the coil is controlled by changing liquid mass flow), or nominal rating point is at different flow rates than under test conditions.
- For the coil validation tests it is quite easy to predict sensible heating and/or cooling loads since they are based on simple energy balances. It is much more difficult to predict latent cooling load due to dehumidification and/or condition of the liquid fluid leaving the coil. This might have a big impact on the assessment of control quality. Such uncertainties also should be taken into account when an overall simulation approach is used to predict the performance of the whole system: Chiller performance would depend significantly on the chilled water parameters leaving the cooling coil and also boiler performance would depend on hot water parameters leaving the heating coil.

ACKNOWLEDGEMENT

Thanks to Curtis Klaassen from the Energy Resource Station (ERS) at Ankeny Iowa that has provided a lot of detailed experimental data used for empirical validation purposes. Special thanks also go to Dr. Greg Maxwell and Som Shrestha of Iowa State University, and Xiaohui Zhou of the Energy Resource Station for their efforts in developing and implementing the mechanical and control systems testing. Thanks also to all people participating in Subtask D for their valuable contributions.

REFERENCES

Felsmann, C.et al: 2008. Mechanical Equipment & Control Strategies for a Chilled water and a Hot water system. Final Report of the IEA Task34/Annex43 Subtask D, Technical University of Dresden, Germany

Lemort, V.; Rodríguez, A. and Lebrun, J.: Simulation of HVAC Components with the Help of an Equation Solver, Faculté des Sciences Appliquées, Département d'Aérospatiale et de Mécanique, Laboratoire de Thermodynamique, 2008