A COMPARISON OF THE ASHRAE SECONDARY HVAC TOOLKIT DETAILED AND SIMPLE COOLING COIL MODELS WITH MANUFACTURERS' DATA

I. KOROLIJA, V. HANBY, L. MARJANOVIC-HALBURD, Y. ZHANG
The Institute of Energy and Sustainable Development, Queens Building,
De Montfort University, The Gateway, Leicester, LE1 9BH, United Kingdom,
Tel: +44 (0)116 2551 551 ext 6848, Fax: +44 (0)116 257 7981, email: ikorolija@dmu.ac.uk

ABSTRACT

Modelling a complete HVAC system requires a detailed knowledge of the system component performance. One of the main components of the HVAC system is the air handling unit (AHU), the essence of which is the cooling coil, a complex component to model. The HVAC Secondary Toolkit, developed by ASHRAE, presents two cooling and dehumidifying coil models; detailed (CCDET) and simple (CCSIM). The CCDET model is suitable for coils for which detailed geometrical data are available, whereas the CCSIM model calculates coil performance based on the coil properties at its rating point.
Data necessary for determining coil geometry have been collected from several manufacturers' catalogues. In addition, some manufacturers also publish the coil characteristics at the rating point, but these data are very limited and cover only a few coils from the whole product range. When available, these data are compared to the CCDET model outputs calculated for the same inputs stated in the manufacturer catalogue. The CCSIM model uses CCDET outputs at the rating point for coil performance calculations. The paper compares the outputs from these two models over the whole range of input variables (mass flow rates, entering temperatures and humidity ratios). Some manufacturers also provide coil selection software which calculates the coil performance at different operating conditions. This paper also compares the outputs from the CCDET coil model using manufacturers' geometrical data with CCSIM coil model outputs, hence providing practical guidance regarding the choice of an appropriate level of modelling when carrying out AHU simulations.

1. INTRODUCTION

The cooling coil forms a crucial link between a cooling load on the one side and a cooling plant on the other side, therefore special attention has to be paid when modelling cooling coils, hence a large number of cooling coil models have been developed. Zhou and Braun (2007) made an historical review of cooling coil model development. Cooling coil models are usually used in two ways; for stand-alone component performance prediction, or as a part of a larger simulation package. Typical examples of such models are two cooling and dehumidifying coil models developed by ASHRAE and presented in the HVAC Secondary Toolkit (Brandemuehl, 1993); the detailed model (CCDET) and the simple model (CCSIM).
HVAC system energy consumption depends on real-world performance. The equipment is chosen by design engineers and has to enable the satisfactory functioning of the system as whole. To provide easy and fast equipment selection, manufacturers publish catalogues with product characteristics and specifications, in the most cases in standardised format, which enables product comparisons between different manufacturers. The standard that is relevant to cooling coils is the ARI Standard 410-2001 (2001).
This paper, after reviewing the two ASHRAE cooling coil models goes on to compare the outputs from these two models over the whole range of input variables (water/air mass flow rates and water/air entering temperatures) with manufacturers' published data. The first comparison is between the CCDET model and the two manufacturers' coil outputs determined under the standard ARI rating conditions. The second is a comparison between the CCDET model, the CCSIM model and the real coil performances calculated at various conditions.

2. CCDET AND CCSIM MODELS OVERVIEW

Both cooling coil models require two sets of inputs. The first set, which is the same for both models, relates to coil operating conditions: water mass flow rate (MLiq), entering water temperature (TLiqEnt), dry air mass flow rate (MAir), entering air dry-bulb temperature (TAirEnt), and entering air humidity ratio (WAirEnt). Both models share the same outputs: leaving water temperature (TLiqLvg), air dry-bulb temperature (TAirLvg), humidity ratio (WAirLvg), total (QTot) and sensible (Qsen) heat transfer rate, and fraction of surface area wet (FWet). The main difference between two is in the second set of inputs, which define model parameters and the level of model complexity. The set of model parameters in the CCDET model is strongly related to the coil geometry, while in the case of the CCSIM model the set is defined by the rated inputs: nominal water mass flow rate (MLiqRat), entering water temperature at rated conditions (TLiqRat), nominal dry air mass flow rate (MAirRat), entering air dry-bulb temperature at rated conditions (TAirRat), entering air humidity ratio at rated conditions (WAirRat), nominal total heat transfer rate (QTotRat), and nominal sensible heat transfer rate (QSenRat).
The detailed coil model CCDET is suitable for use only when a detailed set of coil geometrical data is available, such as coil surfaces, fin thickness and density, tube diameters, number of rows, material conductivity, etc. In general, the complete set of input data is often very difficult to obtain from the manufacturers. However, these data are crucial in determining coil heat transfer characteristics, such as fin efficiency and convection heat transfer coefficients.
The simple coil model CCSIM is well-suited for the analysis of coils for which detailed geometrical data is unavailable. The model assumes that the heat transfer coefficients are constant under all working conditions and calculates them from the performance of the coil at a single rating point. One of the main weaknesses of this model is that it approximates the performance of cooling coil as either completely dry or completely wet, in contrast to the CCDET which calculates coil performances under partially wet conditions as well. Chillar and Liesen (2004) have presented an improved simple model which eliminates this approximation.

3. ARI STANDARD 410-2001: FORCED-CIRCULATION AIR-COOLING AND AIR-HEATING COILS

The purpose of this standard is to establish the following: definitions; classifications; test requirements; rating requirements; minimum data requirements for Published Ratings; etc. Published ratings are of special interest for design engineers due to providing coil performance characteristics, under stated rating conditions, by which a coil may be chosen to fit its application. Ratings within standard conditions are called standard ratings and, according to the ARI Standard 410-2001, "shall be such that any coil selected at random will have a total capacity, when tested, not less than 95% of its published total capacity". The range of standard rating conditions for cold-water cooling coils is presented in the Table 1. The last column shows the standard conditions for which most manufacturers publish coil performances in their brochures. Some manufacturers provide rating/selection software through which the whole range of published ratings is available.
In this study, the coil operating conditions are in the most cases in accordance with the standard rating conditions. The only exceptions are made in the region of low air temperatures combined with the low humidity, as well as in the region of hot and humid air, where the entering air wet-bulb temperatures are out of the range of standard rating conditions. However, the manufacturers also publish coil performance at conditions outside the range of standard rating conditions: these are called application ratings.

Table 1: Range of standard rating conditions

Range of Standard Rating Conditions		**Manufac. data**
Standard air face velocity, std. ft/min [std. m/s]	200 to 800 [1 to 4]	500 [2.54]
Entering air dry-bulb temp., °F [°C]	65 to 100 [18 to 38]	80 [26.67]
Entering air wet-bulb temp., °F [°C]	60 to 85 [16 to 29]	67 [19.44]
Tube-Side fluid velocity, std. ft/min [std. m/s]	1.8 to 8.0 [0.3 to 2.4]	4 [1.22]
Entering fluid temp., °F [°C]	35 to 65 [1.7 to 18]	45 [7.2]

4. CCDET MODEL OUTPUTS VS. MANUFACTURERS PUBLISHED RATINGS FOR 24” X 48” COIL

After extensive research into available manufacturers data, two have been identified as suitable for the purpose of this analysis: those of McQuay and Carrier. A range of 24” height by 48” length coils has been analysed. McQuay published both the coil geometry and the coil outputs in their catalogue (McQuay, 2006) which is also available online. Geometrical data for Carrier coils have been collected from their catalogue (Carrier, 2007a), while the coil performances have been generated using the manufacturer’s software (Carrier, 2007b), which is available as freeware.
The coils analysed are four, six and eight rows deep with 5/8” tubes diameter and fin density of eight and twelve fins per inch (FPI). McQuay offers two types of plate fins, HI-F – high efficiency fins that maximize the heat transfer but increase the airside pressure drop, and E-F – energy efficiency fins that optimize the overall energy performance despite lower heat transfer rate compared to the HI-F fins. On the other hand, Carrier provides only one type of fin. Another important parameter in coil geometry is the number of serpentines (water-side circuits). The half serpentine and single serpentine coils are analysed in this study. The coil operating conditions used in this analysis are in accordance with ARI Standard as presented in the last column in Table 1. The only exception is made for the Carrier coils with 12 FPI, where the air velocity through the coil face area [v_a] is slightly reduced to 2.43 m/s due to a software limitation related to prevention of carry-over of water droplets.
Figure 1 shows a comparison between the CCDET prediction of cooling coil total cooling capacity and the manufacturers’ data. As expected, the HI-F coils have higher cooling capacities than coils with E-F fins. It is interesting to observe that the Carrier coils and McQuay E-F coils have almost the same cooling output regardless of the number of rows, fin densities and the number of serpentines. The consistent over-estimation of the CCDET total cooling capacity can also be observed from Figure 1. The level of cooling capacity results in higher water leaving temperatures, as shown in Figure 2. Also, the condition of the leaving air calculated by CCDET model is much closer to the saturation point in comparison to the manufacturer data.

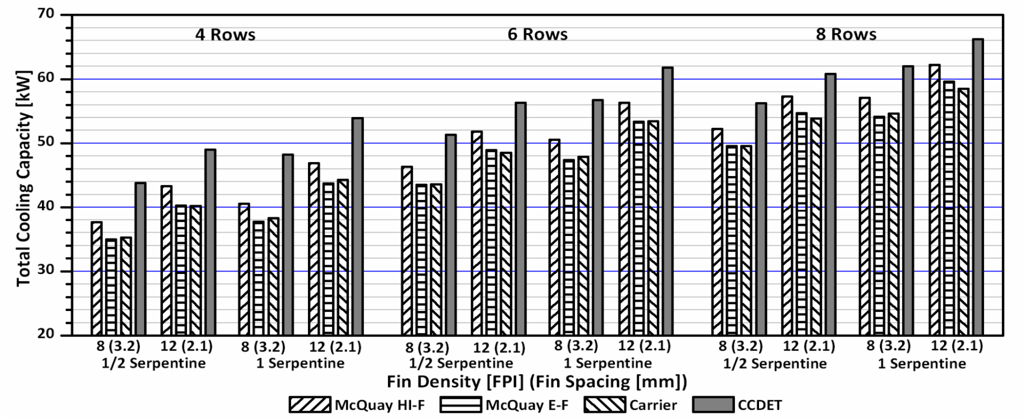

Figure 1: McQuay HI-F / E-F, Carrier, CCDET - total cooling capacity

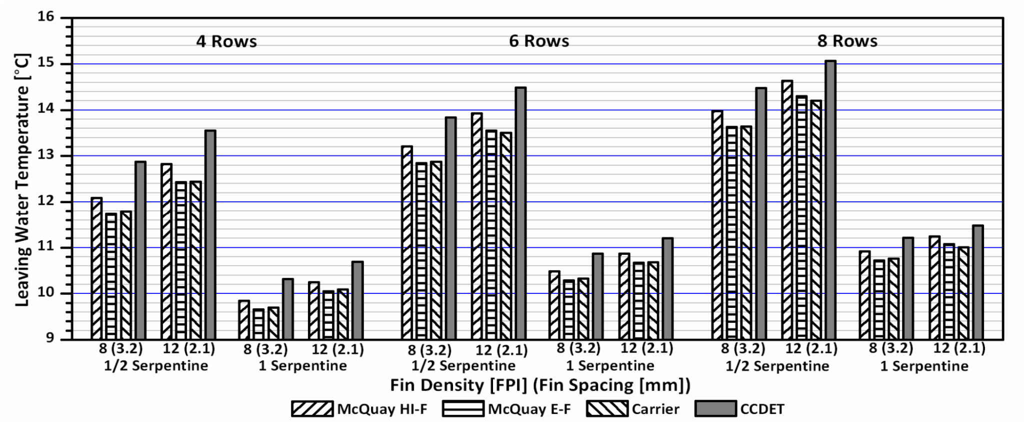

Figure 2: McQuay HI-F / E-F, Carrier, CCDET – leaving water temperature

Figure 3 shows the influence of the number of rows, fin densities and the number of serpentines on the relative difference in CCDET cooling capacity compared to the capacity of the McQuay E-F coil. It can be seen that the relative difference ranges from the around 11% for the eight-row half-serpentine coil with 12 FPI fin density up to 28% for the four-row single serpentine coil with 8 FPI fin density. Higher fin density and more rows leads to a smaller relative difference. The difference is less for the half-serpentine coils than for the single serpentine coils.

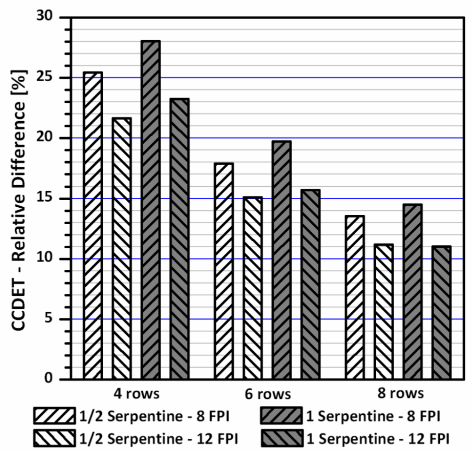

Figure 3: CCDET model - cooling capacity relative difference

5. CCSIM/CCDET MODELS OUTPUTS VS. CARRIER MEDIUM SIZE COIL

A more complex analysis was conducted in this part of the study, based on a coil suitable for installation in a medium size air handling unit. A typical example is the Carrier AHU type 39M – size 12, designed for a nominal air volume flow of 10500 m^3/h. The coil first studied has four rows with ½" tubes outside diameter in a single serpentine arrangement and 11 FPI fin density. Manufacturer coil outputs were calculated using the "Carrier AHUBuilder v5.94" software (Carrier, 2008). The same software was used to determine the rated inputs for the CCSIM model. Coil geometry, used in the CCDET model, was collected from manufacturer's catalogues (Carrier, 2007a), (Carrier, 2007c).
For this analysis the entering water temperature remained constant (7.2°C) while the entering air parameters were varied in following order:

- Entering air dry-bulb temperature: from 18 to 38°C with 4°C increment, and
- Entering air relative humidity: from 30 to 90% with 10% increment.

The first set of results was calculated for the recommended air and water velocities; 2.54 m/s and 1.2 m/s. The shape of the total cooling capacity curves is very smooth and similar for both models as same as for the real coil, which is shown in Figure 4. Figure 5 shows the total cooling capacity relative differences in the CCDET and CCSIM models in comparison to the Carrier coil.

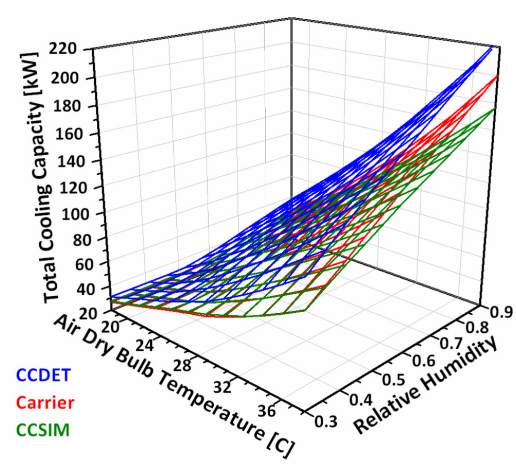

Figure 4: Total cooling capacities

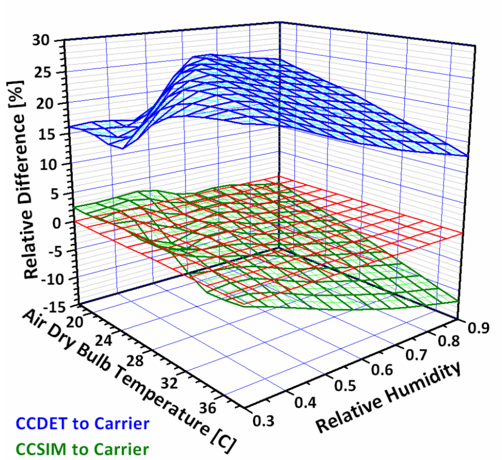

Figure 5: Relative difference – CCDET/CCSIM model outputs to Carrier outputs

As in Figure 1, the results presented in Figure 4 suggest that CCDET always over-estimates the coil total cooling capacity for the given range of temperatures and humidity. The level of over-estimation, shown in Figure 5, amounts to between 16 and 25%. The total cooling capacity calculated by the CCSIM model differs from the manufacturer data by ±2.5% for most of the given range of temperatures and humidity, except in the zone of high air temperatures and humidities, where the relative differences are up to 11%.

To get an overall picture of the relative differences, the analysis was extended to account for the influence of different air and water velocities on the coil performance. The velocity of the air stream was decreased firstly to 2.1 m/s and later to 1.7 m/s. Two additional values of water velocity, 0.8 m/s and 1.6 m/s, were included in the study. Figure 6 and Figure 7 show the behaviour of both models under the new air and water input values. Each graph is composed of nine figures which show the total cooling capacity relative differences for the one set of air and water velocities, combined with different entering air dry-bulb temperatures and relative humidity.

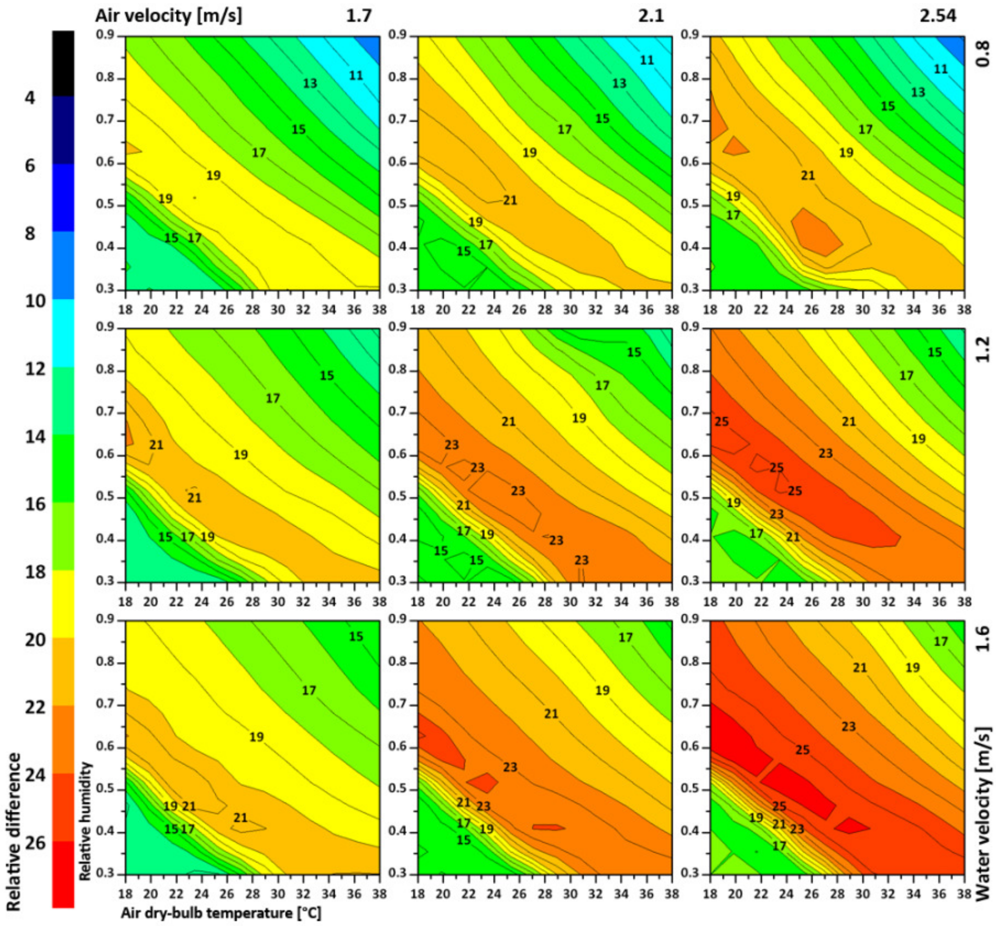

Figure 6: Relative difference – CCDET model outputs to Carrier model outputs / 4 rows coil

Figure 6 presents the total cooling output relative differences between the detailed model and the manufacturer data, which varies between 10 and 25%. In the regions of low air dry-bulb temperatures and humidities, where the coil is completely dry, the difference between model and real coil outputs is considerably lower. The same can be observed for the opposite region of the entering air state, i.e. hot and humid air. A sharp increase occurs when the coil begins to be partially wet and continues to rise until the coil becomes completely wet.

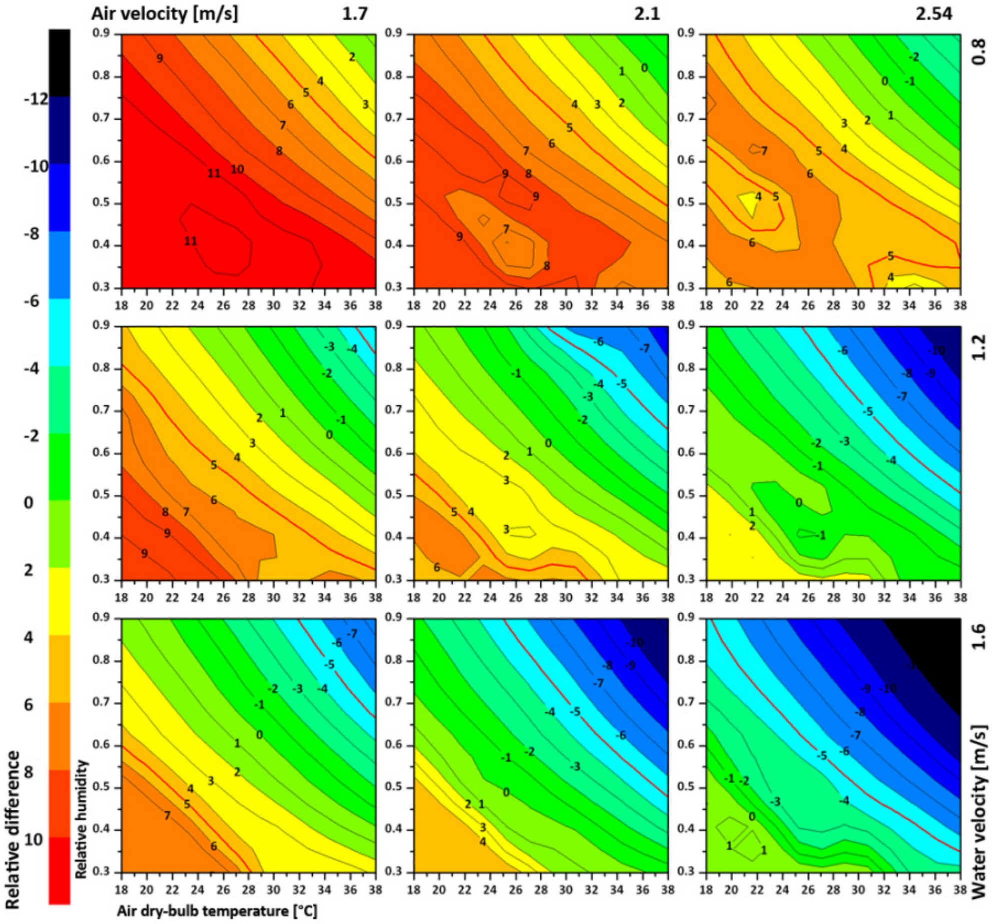

Figure 7: Relative difference – CCSIM model outputs to Carrier model outputs / 4 rows coil

In contrast to the results presented in Figure 6, where CCDET consistently predicts higher total cooling capacities, the results shown in Figure 7 suggest that the simple model relative errors range between -14 and +12%. Total cooling capacity determined by the CCSIM model is higher for lower air and water velocities than the capacity stated by manufacturer. In contrast, if the fluid flows are increased, the coil performance calculated by the model are lower by up to 14% compared to the real coil data.

The explanation of the CCSIM model deviations lies in the fact that the model calculates heat transfer coefficients from the performance of the coil at the single rating point and assumes a constant value regardless of all other conditions. The most obvious example is the influence of the air volume flow decrement and the water velocity changes on these deviations. Due to the rating air velocity of 2.54 m/s, the heat transfer coefficients used in the model are based on that value. However, decreasing the air stream velocity has a direct impact on the air-side convective heat transfer coefficient, which influences the total cooling capacity. Therefore, reducing the total cooling capacity is more rapid for the real coil than for the CCSIM model. Because of that, the relative error increases with lower air velocity. The same argument can be applied to the influence of the water velocity changes to the cooling outputs through the water-side heat transfer coefficient.

In the analysis of the results for 24"x48" coil presented in Figure 3, it was concluded that the difference in total cooling capacities between CCDET and manufacturer is lower for coils with larger number of rows. To confirm that statement, and to show the behaviour of the CCSIM model as well, one more coil was analysed. The coil belongs to the same series of Carrier coils suitable for instalment in the AHU size 12, with ½" tubes outside diameter in the single serpentine arrangement with 11 FPI fin density. The only difference is in the number of rows which was increased from four to eight. The graphs in Figure 8 and Figure 9 visualise both models' total cooling capacity relative differences.

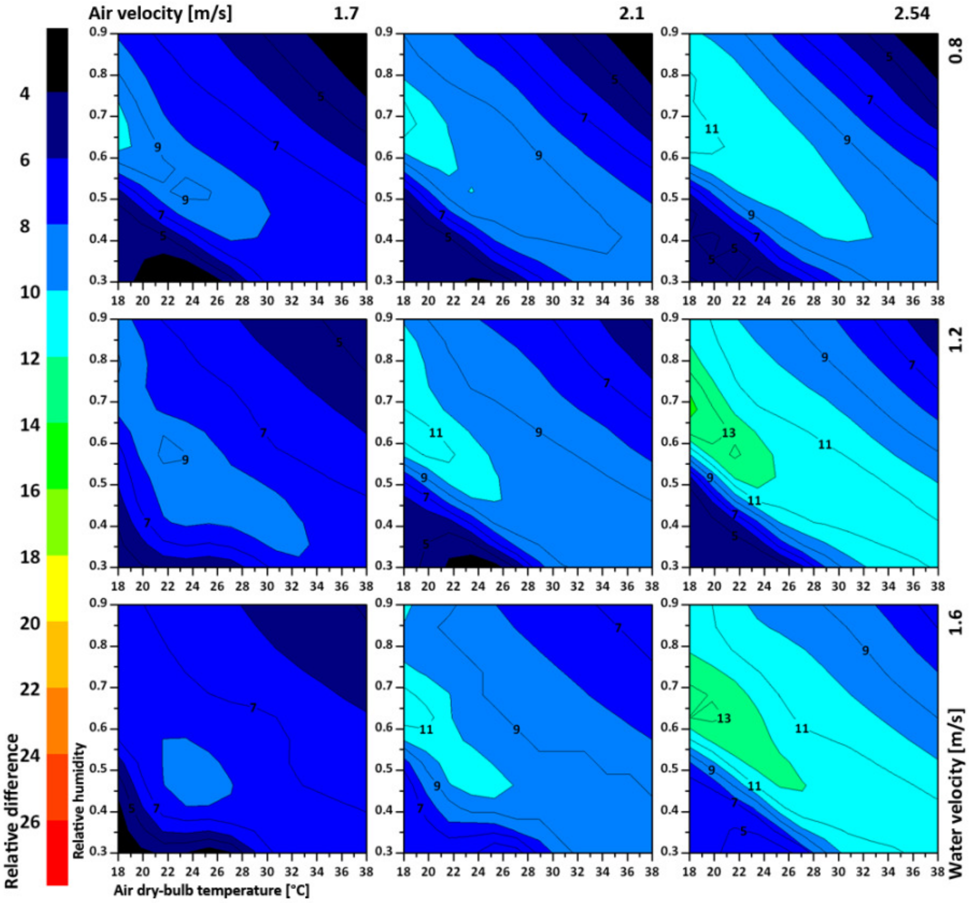

Figure 8: Relative difference – CCDET model outputs to Carrier model outputs / 8 rows coil

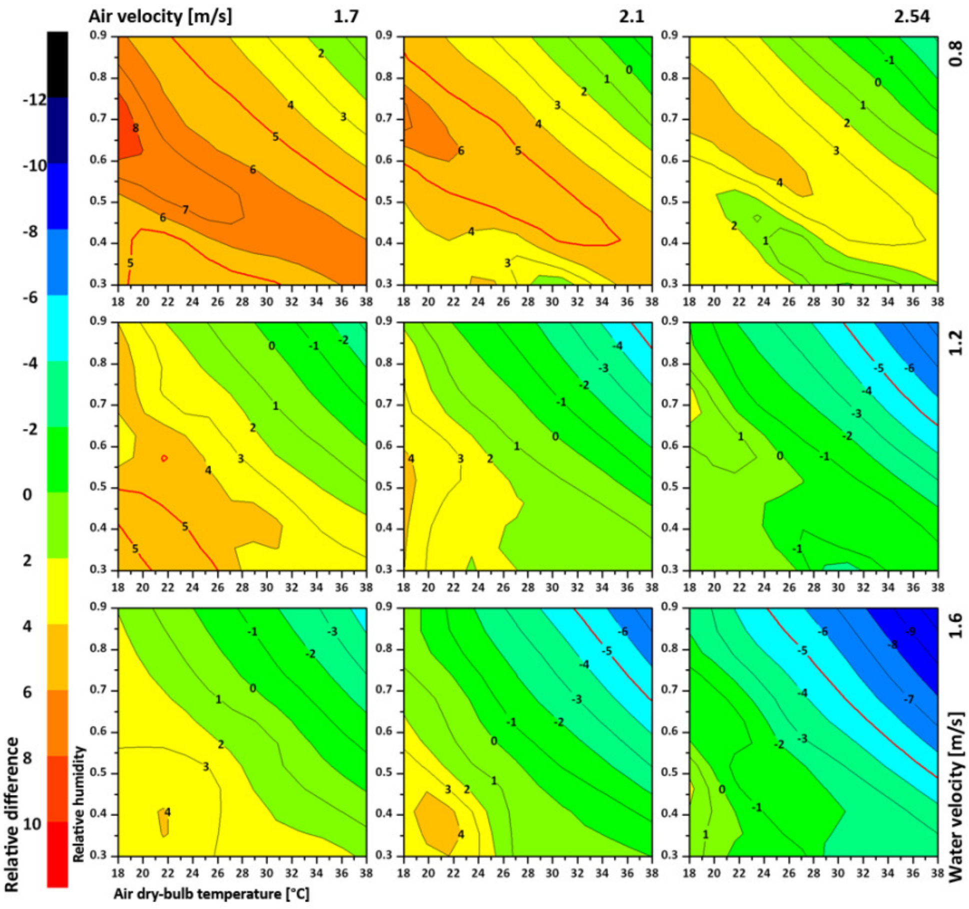

Figure 9: Relative difference – CCSIM model outputs to Carrier model outputs / 8 rows coil

The shape and the nature of the relative differences for both models, CCDET and CCSIM, are almost identical to the coil with four rows. However, there are some differences. The relative difference in the CCDET model is significantly lower in comparison to the difference in the four-row coil and it is less than 10% over most input variables. Slightly higher differences, up to 14%, occur at higher air and water velocities, but only in the area where the coil operates under partially wet conditions. The difference between CCSIM model prediction and manufacturer data is also smaller (in the range of ± 5% for almost all conditions) with only two exceptions. The first is for very high water and air velocities combined with high air temperatures and high humidity, where the relative difference goes up to -8.5%. The second deviation is for low air and water velocities where for almost all air temperatures and humidities other than the very high temperatures/humidity zone, the relative difference is between 5% and 8.5%.

One of the reasons why the results of both models for the eight-row coil are more accurate than for the four-row coil most likely lies in the type of heat exchanger configuration used in the CCDET and CCSIM models. Both models approximate the coil as a counterflow heat exchanger and use the appropriate relations for that type of heat exchanger to determine coil outputs. On the other hand, the real process which occurs in the coil is better represented by the counterflow-crossflow heat exchanger configuration. However, an increase in the number of rows reduces the significance of this approximation.

6. CONCLUSION

The general conclusion of this paper is that the simple cooling coil model, CCSIM, has a slightly better overall performance in comparison to the CCDET model. One of the main advantages is that the inputs are very simple and can be easily obtained. The outputs from this model, in comparison to the real manufacturer data, are more accurate than CCDET outputs and they satisfy the ±5% relative difference for the greater range of input variables. On the other hand, the collection of all necessary data for the detailed coil model inputs is a difficult and sometimes infeasible task. In addition, the CCDET model outputs, despite the calculation procedure being based on a more rigorous theoretical approach, have significant deviations compared to the real coil. However, these deviations are reduced to a certain degree for coils with higher number of rows.

The detailed analysis presented above will be extended in future work. This will include extending the range of manufacturers' data used in the comparison. The exact circumstances under which this information is obtained are often unclear, hence independent test data will also be included.

7. REFERENCES

1. ARI Standard 410-2001. 2001, *Forced-Circulation Air-Cooling and Air-Heating Coils*, Air-Conditioning and Refrigeration Institute, 4301 North Fairfax Drive, Suite 425, Arlington, VA 22203, U.S.A.
2. Brandemuehl M J. 1993, HVAC 2 Toolkit: A Toolkit for Secondary HVAC System Energy Calculations, ASHRAE, Atlanta, GA.
3. Carrier Corporation. 2007a, *Product Data: 28BC,BH,BB,BD,BF,BX,BZ Nu-Fin Separate Sale Plate Fin Water, Direct Expansion and Non-Freeze Steam Coils*.
4. Carrier Corporation. 2007b, *Carrier Electronic Catalog: Separate Sales Coil Selection v1.06*.
5. Carrier Corporation. 2007c, *Product Data: 39MN, MW03-61 AERO Indoor and Weathertight Outdoor Air Handlers, 1,500 to 30,500 Nominal Cfm*.
6. Carrier Corporation. 2008, *Carrier Electronic Catalog: AHUBuilder v5.94*.
7. Chillar R J, Liesen R J. 2004, Improvement of the ASHRAE Secondary HVAC Toolkit simple cooling coil model for simulation, *SimBuild 2004*, IBPSA-USA National Conference. Boulder, CO.
8. McQuay International. 2006, *Catalog 411-7: McQuay Water Cooling & Evaporator Coils – Types HI-F5 & E-F5*.
9. Zhou X, Braun J E. 2007, A simplified dynamic model for chilled-water cooling and dehumidifying coils - Part 1: Development (RP-1194), *HVAC and R Research* 13(5): 785-804.

8. AKNOWLEDGEMENT

The authors would like to acknowledge financial support of this work which forms part of the CITYNET project funded via the Marie Curie Research Training Network.