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AUTOMATIC ANALYSIS AND CORRECTION OF HVAC SYSTEM SIMULATED PERFORMANCE: A COOLING COIL CASE STUDY

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ABSTRACT

Current HVAC system simulation software is sufficiently accurate and flexible to be of use in system design. Its integration into the design process is hindered, however, by the need for extensive analysis of the simulation output and by difficulties in taking action to correct system performance if this is initially poor. The first section of this paper gives an overview of the use of intelligent knowledge-based software in the automatic analysis and correction of the simulated performance of HVAC systems. The second section describes an implementation for the steady-state simulation of a proportionally controlled cooling coil.

INTRODUCTION

Recently, there has been a rapid expansion in the development of software for the simulation of the thermal performance of heating, ventilating, and air-conditioning (HVAC) systems (Murray 1985; Day et al. 1986; Clark and May 1985; Sowell et al. 1986). Much of the research to date has been concerned with the development of modeling and solution procedures, and, although a user-simulation interface has been developed (Clarke and Rutherford 1988), attention has only recently been paid to the way in which the software is used to perform the analysis and improve designs. This has led to software that is very sophisticated in terms of modeling flexibility but gives little assistance in the analysis of results or guidance on possible improvements in system design.

HVAC System Simulation and Design

HVAC system performance simulation software is used at an early stage of design to predict the performance and operation of the system. This is particularly important in relation to novel and innovative designs, where experience with the installed performance of the system is unknown or limited. The first step in a simulation exercise is to define the system configuration, set design conditions (such as fluid mass flow rates), and select appropriate sizes of components. The selection of the design conditions and component sizes is normally made through a conventional working design procedure in isolation of the simulation. Following the simulation of system performance, two operations are required to improve the system design:

1. The operation and performance of the individual components and of the system as a whole are analyzed and an assessment is made as to the suitability of the system.
2. If the system performance is unsatisfactory, then it is corrected by changing the size of the system components and/or design conditions. In some instances, it may be necessary to select a different system type.

Once the corrections have been made, the system performance can be re-simulated and re-analyzed, with further corrections and analysis made if necessary. This iterative process is time-consuming, requires in-depth knowledge on behalf of the user, and often involves operations that are external to the simulation, such as cross-references to manufacturers' catalogs in order to make improved equipment selections. It is evident that the effectiveness of the simulation software as a design tool can be improved by automating the analysis and correction of the system's performance.

AUTOMATIC ANALYSIS AND CORRECTION OF SYSTEM PERFORMANCE

There is no generalized approach to analyzing and correcting the simulated performance of HVAC systems. Each user of the software will adopt a different and in some cases arbitrary or trial-and-error approach that is directed more by intuition than by fact. The factors considered by the users will vary according to the project at hand; for instance, system efficiency may be of little importance so long as close control is maintained.

Analysis of Design Conditions and HVAC System Performance

HVAC system simulated performance cannot be analyzed in complete isolation from the choice of design conditions and the form of simulation. Three levels of analysis can therefore be identified:

1. Analysis of the cause of failure of the simulation, should this occur.
2. Analysis of the system's performance.
3. Analysis of the choice of design conditions and component selections.

Failure of the Simulation Failure of the simulation is often due to the poor sizing of components or bad choice of design conditions, as this can produce an insoluble set of system equations. The cause of failure may be identified from the simulation output, as it is often evident that the solution had placed the operating point of a component beyond its performance limit. The extent to which any output from a failed simulation is of use depends upon the particular simulation solution procedure. In some instances, it is possible to assess the choice of component size and design constraints (such as the fluid velocities at peak flow).

Analysis of System Performance HVAC system performance is defined here to mean the operation and efficiency of the system. Four factors are often considered in relation to system performance:

1. The maintenance of system control for both individual components and, in sequencing of control, from one component to another (local loop and supervisory control).
2. The compliance with design constraints, such as limiting fluid velocities.
3. The provision of acceptable residual operating capacity.
4. Efficient and economical system operation.

Many of these factors can be assessed for each component and judged against a readily available rule of thumb. Those factors that are assessed at system level are, however, less generally defined and can be specific to a particular system's configuration. The sequencing of control, for instance, is specific to the type of air-conditioning system.

Analysis of the Design Conditions and Component Size

The separate analysis of the design conditions and component size is important on two accounts: First, to interpret the cause of any poor performance, which is often less than obvious and always involves some inference. Second, the choice of design conditions and component selections must be assessed against current working practice, since it is possible that a bad combination of design conditions and component sizes could produce a seemingly satisfactory performance. Rules of thumb are available for evaluating the design conditions, but few or no rules of thumb are available for assessing the physical size of the components. Rules for analyzing component size could be formulated by relating the component's operating point to the limits of its performance map or through developing a size descriptor from first principles.

HVAC System Performance Correction

Correction of system design follows the performance analysis. Providing that a change in system type is not suggested, the system performance can be corrected by changing the values of the design conditions and by resizing the components. Rules of thumb are available for evaluating the design conditions, but few, if any, simple rules exist for specifying the physical size of the components.

The correction to system performance is further complicated by the thermofluid coupling between the components, as though this change to one component or design condition will affect the performance of other components in the system. This effect also applies to individual components when the component size is described by more than one parameter.

The correction process itself can be approached in several ways: the correction of component size and the design parameters could be based on simple rules formulated in association with the rule for assessing performance. A second possible approach is to implement the component selection procedures employed by the equipment manufacturers to produce working designs. Finally, the correction could be based on an optimal design procedure, which, for example, gives solutions with the lowest capital cost.

Implementation for Automatic Analysis and Correction

Both analysis and correction of system performance require large amounts of expertise and knowledge. Much of this knowledge can be represented by simple rules and facts and through inference. Whereas most simulation software is written in a procedural programming language, the facts, rules, and inference required for the analysis and correction of system performance are best implemented using an intelligent knowledge-based language. If the optimal correction of system performance is required, additional procedural calculating routines are necessary to perform the optimization. These routines could be directed or accessed by the intelligent knowledge-based software. The interfacing of two different languages can be difficult, although in most cases either the languages will permit this directly or the linking can be achieved through the computer's operating system. Each simulation program has its

own component model format, system definition procedure, and solution procedure. Due to these differences, any automatic performance analysis and correction procedure will be specific to the simulation program. This is not to say that a basic template containing the knowledge common to all simulation programs could not be developed.

COOLING COIL CASE STUDY

The attributes of the automatic analysis and correction process have been informed through a cooling coil case study (Boughazi 1989). Figure 1 illustrates the system simulated. The coil is proportionally controlled by the action of a three-port diverting valve; the control variable is the dry-bulb temperature leaving the coil. The size of the coil is defined by the number of rows, number of water circuits, and the coil's width and height; the fin spacing is fixed in the simulation at 315 fins/m. The air condition entering the coil and water inlet condition to the valve are defined by the user, as are the setpoint and proportional band of the controller. The hydraulic performance of the system is excluded from the simulation; the control valve is, therefore, assumed to have a linear installed characteristic.

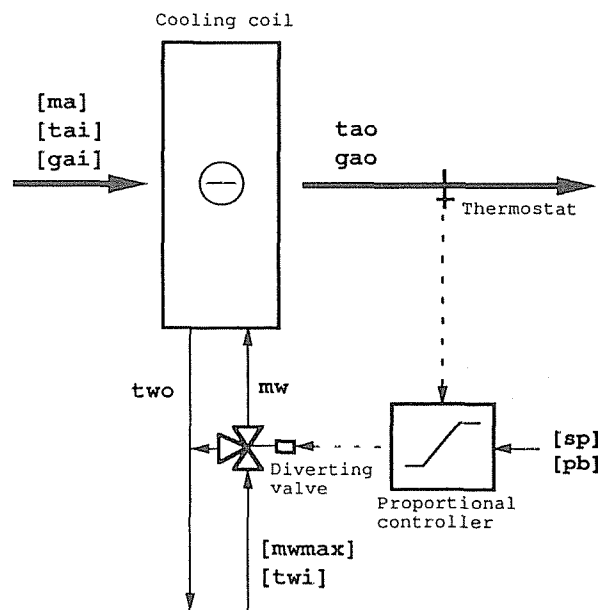


Figure 1 Proportionally controlled cooling coil. Variables in [] are fixed during the simulation.

The objective of the study is to investigate the feasibility of analyzing and correcting the peak-load performance of the coil using only simple rules of thumb rather than extensive design calculations. The coil's performance is defined in terms of:

1. Maintenance of control (steady-state control error).
2. Compliance with air face and water velocity limits.
3. Provision of acceptable residual operating capacity.

The analysis of the design conditions and component size is restricted to:

1. The water flow rate at peak load.
2. The coil size, which is not defined in relation to any specific dimensions but is implied to mean the total heat transfer surface area.

The parameters that can be changed to correct an indicated poor performance are:

1. The water mass flow rate at peak load.
2. The coil width, height, number of rows, and number of water circuits.

The Simulation Model

The simulation model implemented is steady state and is based on the British Standard test and performance calculation method (B.S. 5141, 1975). The standard adopts the "three line" calculation method, which simulates three modes of heat transfer on the air side of the coil: a dry surface, a partially wet surface, and a wet surface. The system performance is simulated by using a successive approximation algorithm to iterate on both the coil water mass flow rate and the coil air outlet temperature. The simulation is generally robust, although it can fail when the operation of the coil lies between modes of heat transfer (e.g., between a wet or partially wet surface) or when the operation is outside the limit of the modeled range of heat transfer coefficient on the air side of the coil (a face velocity of more than 5.0 m/s).

Knowledge Acquisition, Simplifying Assumptions, and Limitations

Rules for the analysis and correction of cooling coil performance have been obtained from published rules of thumb (Hayward 1988) and through a knowledge of cooling coil design in practice and through experience in operating the simulation.

In order to reduce the scope of the analysis and correction to a manageable level, several simplifying assumptions have been made. The effect of the controller's proportional band is not analyzed, nor is it used to correct system performance since its effect on the system's stability is not reproduced by the steady-state simulation. Similarly, the suitability of the coil flow water temperature is not considered in the analysis or during performance correction, since its effect on chiller performance cannot be assessed as the chiller is not part of the system simulated. Finally, the analysis and correction are for the peak load on the coil, as this is when the coil performance is tested to its limit.

The size of a coil is not only described by the physical width, height, and number of rows but also by the number of water circuits. The correctness of coil size in relation to any one of these parameters is influenced by one or more often-competing design constraints. The coil height, for instance, can be dictated by the amount of heat transfer surface area required to maintain control as well as the limiting face velocity. In light of these difficulties, the analysis and correction of coil size has been simplified. The analysis of size is purely through inference, with coil "size" implied to mean the total heat transfer surface area. The correction procedure for the physical size of the coil is similar to cooling coil design methods in practice; namely, width and height are used to correct the coil face velocity, the number of water circuits to correct the water velocity, and the number of rows to correct the heat transfer surface area.

The cause of the simulation failure is not included in the automatic analysis. The parameters that can be assessed on failure of the simulation are the maximum air face and water velocities and the choice of maximum water flow rate.

Rules for Performance Analysis

The parameters included in this analysis are: maintenance of control in the steady state, the compliance with design constraints, and the coil's residual operating capacity.

Maintenance of Control Under peak load conditions, the control valve will be fully open, the mass flow rate will be at its maximum value, and the control variable will be on the limit of the proportional band (Figure 2). Hence, control is maintained provided that

$$tao \leq sp + pb / 2.$$

Rules for the Analysis of Design Constraints The only design constraints that are considered in this study are the air face and water velocities. In general, the air velocity is considered to be acceptable if it is less than or equal to 2.5 m/s; above this velocity, the excessive pressure loss, noise, and moisture

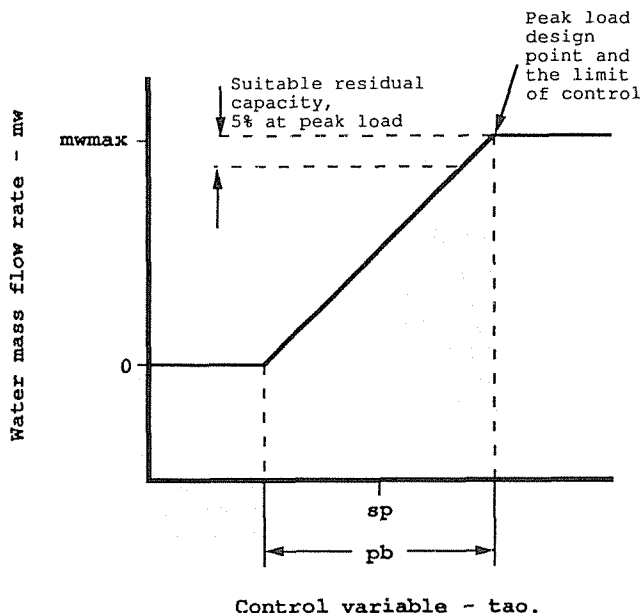


Figure 2 Limit of control and definition of residual capacity

carryover can be a problem. The maximum water velocity per water circuit is acceptable if it is less than or equal to 1.8 m/s; at velocities greater than this, erosion of the pipework can occur. The maximum water velocity occurs when the control valve is fully open and the water flow rate is at its maximum. Since the valve may not be fully open for the simulated load, the maximum water flow rate is used to calculate the water velocity constraint.

Rule for the Analysis of Residual Capacity It is desirable to select HVAC components with an amount of residual operating capacity to allow for the deterioration in performance with use and the occasional excessive loads. The residual operating capacity of a cooling coil should be described by its physical size and the water flow conditions. However, if the analysis is for the design peak load on the coil, the valve position under this load is indicative of the residual capacity of the coil. Therefore, in this study, the residual capacity of the coil is judged to be satisfactory if the actual water mass flow rate is within 5% of the maximum (Figure 2):

$$[(mw - mwmax) / mwmax] \leq 0.05.$$

The 5% limit is arbitrary and could be different in other studies.

Rules for the Analysis of the Design Condition

The design parameter or condition in this study is restricted to the maximum water mass flow rate entering the coil; the value chosen for this parameter influences the size and operation of the coil. A suitable water flow rate at peak load is given by Hayward (1988); this will give a temperature rise in the chilled-water temperature of approximately 6.0°C:

$$mw_{peak} = 0.042 Q_{t}.$$

The maximum water mass flow rate to the coil is assumed to be correct if it is within 10% of the rule-of-thumb value, mw_{peak} :

$$-0.10 \leq [(mwmax - mw_{peak}) / mw_{peak}] \leq 0.10.$$

Again, the 10% limit is arbitrary and could be changed in other studies.

The calculation of Q_t depends on the simulated operating point of the coil. If the simulation succeeds and steady-state control is maintained, then the duty of the coil returned by the simulation will be the true peak load of the coil. However, where steady-state control is not maintained, the coil duty returned by

the simulation will be less than the true peak duty; here, the peak duty can be estimated from:

$$Q_t = ma \text{ Cp } (sp - tai) / shr.$$

If the simulation should fail, then the sensible heat ratio is unavailable and an "in the order of" value must be defined. The value of 0.6 has been selected as a typical sensible heat ratio for this study.

Rules for Analyzing Coil Size

Coil "size" is implied here to mean the total heat transfer surface area. Since few, if any, simple rules of thumb exist for assessing coil size, the approach adopted in this study is to use inference to judge the suitability of coil size. The performance of a coil is dependent on both the water mass flow rate and coil size. The choice of coil size can, therefore, be inferred from the coil performance and choice of water flow rate, since these can be separately analyzed. For instance, if the coil performance is correct and yet the water mass flow rate is found to be low, then the coil must be oversized to compensate for the reduced water mass flow rate. This approach is limited on two accounts: First, the coil size cannot be analyzed in all cases, most notably, if the coil performance is poor and the water mass flow rate is low, then it is not possible to infer that the coil is also undersized. Second, the individual parameters of coil size, such as width and height, cannot be assessed in relation to the amount of heat transfer surface area. The rules for coil size analysis are as follows:

The coil size is correct if control is maintained, the residual capacity is correct, and the water mass flow rate is correct.

The coil is undersized if control is maintained, the residual capacity is correct, and the water mass flow rate is high, or, if control is not maintained and the water mass flow rate is high or correct.

The coil is oversized if control is maintained and the water mass flow rate is low, or, if control is maintained, the residual capacity is high, and the water mass flow rate is correct.

Rule for Correcting the Design Condition

The maximum water mass flow rate to the coil can be reset by assigning it the value derived from the rule of thumb used in the analysis:

$$mw_{max} = mw_{peak}.$$

Rules for the Correction of Coil Size

The correction of coil size could be initiated either directly from the analysis of size or in order to correct an indicated poor performance. Since coil size is defined by several parameters and no simplified rules exist for correcting coil size, the source of correction for each parameter has been selected in relation to current working practice. The main elements are that coil width and height are corrected to give a satisfactory face velocity; the number of water circuits is corrected to produce a satisfactory water velocity; and the number of coil rows is adjusted to correct an indicated under- or oversizing of the coil.

Correction to Coil Width and Height The coil width and height are corrected to give a face velocity equal to the limiting velocity. To simplify the calculation, a square face area is assumed:

$$Af = ma \cdot spvol / vf$$

$$\text{Width} = \text{Height} = Af^{0.5}.$$

Correction to the Number of Water Circuits The number of water circuits is corrected to give a water velocity equal to the limiting velocity:

$$Nc_{irc} = mw_{max} / \rho \cdot Ai \cdot vw.$$

Correction to the Number of Coil Rows The rules of thumb for correcting coil size have been developed more through intuition than adherence to standard design methods. The particular rule applied for correction depends on the inference used to identify incorrect sizing. The strategy for correcting an undersized coil is as follows:

If control is maintained but the water mass flow is high, then the coil rows can be increased in proportion to the proposed reduction in water flow rate, provided that the correction is not so great that the nonlinearity in the relationship between coil output, water mass flow rate, and the number of rows becomes significant:

$$Nrow = Nrow [1 + (mw_{max} - mw_{peak}) / mw_{max}].$$

Where control is not maintained and the water mass flow rate is correct or high, then a better indication of the correction to the number of rows required is by a comparison of the air outlet temperature and the setpoint temperature. The water inlet temperature is also included in this rule, since the difference between the air and water temperature is an indication of the driving force for heat transfer:

$$Nrow = Nrow (tao - twi) / (sp - twi).$$

Similarly, in correcting an oversized coil, the strategy depends on the inference used to identify oversizing. The strategy for correcting oversizing is as follows:

If control is maintained but the maximum water mass flow rate is low, then the number of coil rows can be corrected in proportion to the proposed increase in water mass flow rate:

$$Nrow = Nrow (mw_{peak} - mw_{max}) / mw_{max}.$$

Where control is maintained, the water mass flow rate is correct, but the residual capacity is high, then the coil rows can be decreased in proportion to the required reduction in residual capacity. Since the residual capacity is defined in terms of the actual and maximum possible water flow rates through the coil and as the flow rate is to be within 5% of the maximum, then the correction to the number of rows is given by:

$$Nrow = Nrow [mw / (0.95 \cdot mw_{max})].$$

Implementation

The rules for analysis and correction have been implemented using the declarative programming language PROLOG. This is interfaced to the cooling coil simulation written in FORTRAN by a routine written in ASSEMBLER. A mainframe computer has been used to run the software. The software is entered through the PROLOG routines, and a menu structure allows program control. The user may specify the peak load on the coil and the coil width, height, number of rows, and number of water circuits for the initial analysis and correction.

Following an initial analysis of performance, the user may correct a single parameter (such as coil size), after which the simulation is re-run and the performance re-analyzed. A "correct-all" option corrects each parameter in turn, re-running the simulation and re-analyzing performance after each correction. The process iterates until the parameter is correct. The order of correction is:

1. Width and height based on the face velocity.
2. Number of water circuits based on the water velocity.
3. Number of rows based on the coil size as analyzed.

The backward-chaining inference mechanism of PROLOG is suited to the task of performance analysis and correction, although a forward-chaining mechanism may simplify the implementation for interpreting the cause of an indicated poor performance.

TABLE 1
Example Coil Load Data

Variable	Data
<i>ma</i>	6.5 kg/s
<i>tai</i>	28.0°C
<i>gai</i>	0.0145 kg/kg
<i>twi</i>	8.0°C
<i>sp</i>	12.0°C
<i>pb</i>	1.0°C

TABLE 2
Example Coil Sizes and Design Conditions for Analysis
(Example 3 represents the "ideal" solution)

Example	Number of Coil Rows	Coil Width (m)	Coil Height (m)	Number of Water Circuits	Maximum Water Mass Flow Rate (kg/s)
1	5	1.52	1.52	26	12.0
2	5	1.52	1.52	26	5.0
3	5	1.52	1.52	26	8.1
4	10	2.00	2.00	10	12.0
5	10	1.52	1.52	25	5.0
6	10	2.00	2.00	26	8.1
7	2	1.00	1.00	10	12.0
8	2	1.00	1.00	26	5.0
9	2	1.52	1.52	26	8.1

Example Analysis and Correction

The effectiveness of the software in performing the analysis and correction has been tested against several examples. The load on the coil and the controller setpoint remain the same in each example presented here (Table 1). Table 2 gives the example coil sizes and water mass flow rates. Table 3 presents the output from the simulation for each example; the output data are incomplete for examples 4 and 7, since the simulation failed to find a solution, limiting the usable output data. Table 4 gives the conclusions drawn from the analysis and the correct, or expected, conclusions where this differs. Table 5 gives the coil sizes after the correction process.

The examples have been selected to test all possible combinations of high, low, and correct maximum mass flow rate, with oversized, undersized, and correct coil size (Table 4). Conditions to test the conclusions drawn for coil performance are scattered arbitrarily within the set of examples. Example 3 represents the "ideal" solution, since this coil's performance and size are "satisfactory."

Analysis of Coil Performance In general, the rules for analysis proved to be satisfactory, with the only major limitation being the ability to evaluate coil size (heat transfer surface area) for all conditions. Where the simulation fails to find a solution (examples 4 and 7), it is not possible to assess the level of

control, residual capacity, or coil size, since the data available for analysis are insufficient. Two minor errors were identified after the implementation of the software, namely, that a check for low water and air face velocity is not included in the analysis; similarly, the analysis does not check for an insufficient residual capacity. These simplifications account for the differences between the expected and actual conclusions for these parameters (Table 4).

The rules for assessing the choice of water mass flow rate have been successful, except for example 8, where the coil was so undersized that only sensible cooling occurred, giving a reduced coil duty and assessment of mass flow rate. This error can be corrected by setting a typical coil sensible heat ratio when the simulation shows no dehumidification but dehumidification is expected.

The inference-based rules for analyzing coil size proved to be limiting in three examples. In example 1, it is not possible to infer if the high residual capacity of the coil is a result of both the water mass flow rate and coil size; indeed, if the water mass flow rate is high enough, then the coil could even be undersized. Similarly, if the water mass flow rate is low and the residual capacity is low or correct and control is lost (as in example 2), then it is impossible to infer if the lack of control is also due to an undersized coil. This would also apply to example 8 had the water mass flow rate been judged as low instead of correct. In this case, example 8 illustrates that rules that rely purely on inference can draw incorrect conclusions when an error in a preceding judgment is made.

Correction to Coil Size and Water Mass Flow Rate Table 5 gives the final corrected coil sizes and water mass flow rates and the number of times the coil performance was re-analyzed to reach the final corrected conditions. The correction to water mass flow rate was successful in all examples except example 7; here the water mass flow rate is 12% higher than the correct value, although it is within 10% of the calculated rule-of-thumb value against which it was assessed. The oversized coil width and height in examples 4 and 6 were not corrected, since the correction is based on the coil face velocity and no rules were included to indicate a low face velocity with consequent oversized width and height. The correction to the number of water circuits was successful in all examples.

The correction to the number of coil rows was successful except where the coupling between the coil width, height, and number of rows became critical. In examples 4 and 6, the width and height were oversized, which led to a reduction in the number of coil rows and a final judgment of an oversized coil. Similarly, in example 8, the width and height are slightly less than the ideal solution (example 3), which led to an increase in the number of rows. The conclusion here is that although the rules for correcting coil size are suitable for making crude corrections, the coupling between coil width, height, water circuits, and water mass flow rate must be considered in order to achieve a final correct solution.

TABLE 3
Simulation Output Data

Example	Simulation Solution Found?	Control Variable (<i>tao</i> , °C)	Air Face Velocity (m/s)	Maximum Water Velocity (m/s)	Water Mass Flow Rate (<i>mw</i> , kg/s)	Rule of Thumb Flow (<i>mwpeak</i> , kg/s)	Sensible Heat Ratio (<i>shr</i>)	Duty (kW)
1	YES	12.2	2.5	1.8	8.6	8.4	0.5	201.6
2	YES	14.4	2.5	1.1	5.0	8.5	0.5	165.6
3	YES	12.5	2.5	1.7	8.0	8.3	0.5	197.7
4	NO	—	1.4	6.6	—	7.7	—	—
5	YES	12.4	2.5	1.1	4.2	8.2	0.5	195.8
6	YES	11.9	1.4	1.7	4.1	8.5	0.5	203.2
7	NO	—	5.7	6.6	—	7.7	—	—
8	YES	18.4	5.7	1.1	5.0	4.6	1.0	63.5
9	YES	18.5	2.5	1.7	8.1	8.7	0.5	117.2

TABLE 4
Conclusion Drawn by the Analysis
(Expected conclusions are enclosed in brackets where they differ from the actual conclusions)

Example	Air Face Velocity	Maximum Water Velocity	Control	Residual Capacity	Maximum Water Mass Flow Rate	Coil Size
1	Satisfactory	High	Maintained	High	High	No conclusion (Correct)
2	Satisfactory	Satisfactory (Low)	Not maintained	Correct (None)	Low	No conclusion (Correct)
3	Satisfactory	Satisfactory	Maintained	Correct	Correct	Correct
4	Satisfactory (Low)	High	No conclusion (Maintained)	No conclusion (High)	High	No conclusion (Oversized)
5	Satisfactory	Satisfactory (Low)	Maintained	High	Low	Oversized
6	Satisfactory (Low)	Satisfactory	Maintained	High	Correct	Oversized
7	High	High	No conclusion (Not maintained)	No conclusion (None)	High	No conclusion (Oversized)
8	High	Satisfactory (Low)	Not maintained	Correct (None)	Correct (Low)	Undersized
9	Satisfactory	Satisfactory (Low)	Not maintained	Correct (None)	Correct	Undersized

TABLE 5
Coil Size and Design Condition after Automatic Correction

Example	Number of Coil Rows	Coil Width (m)	Coil Height (m)	Number of Water Circuits	Maximum Water Mass Flow Rate (kg/s)	Number of Iterations
1	5	1.52	1.52	27	8.4	2
2	5	1.52	1.52	27	8.5	2
3	5	1.52	1.52	26	8.1	0
4	4	2.00	2.00	24	7.7	4
5	5	1.52	1.52	26	8.2	4
6	4	2.00	2.00	26	8.1	2
7	5	1.51	1.51	28	9.1	5
8	6	1.51	1.51	26	8.1	4
9	5	1.52	1.52	26	8.1	1

CONCLUSIONS

The conclusion of this research is that it is feasible and beneficial to develop a knowledge-based program for the automatic analysis and correction of HVAC system simulated performance, although the effectiveness of implementing simple rules of thumb is reduced when the coupling between the system design parameters is not modeled. This study has been restricted to the performance analysis and correction of a proportionally controlled cooling coil operating at peak load. Although the study is for a single component, the design of a cooling coil is sufficiently complicated for the coupling between the design parameters of the coil dimensions and the maximum water mass flow rate to be representative of the characteristic problems associated with analyzing and correcting larger systems.

Two levels of analysis have been identified: first, the analysis of system operation and performance, and second, the analysis of the design conditions and component sizes. The rules implemented for assessing the performance of a cooling coil proved to be reliable, except in assessing the suitability of component size (heat transfer surface area). Here the analysis is based on inference that has limited the range of conditions under which an assessment can be made. A more suitable approach would be to develop rules for analyzing size that rely on explicit relationships including the coupling between the variables. This would also have the advantage that the effect on coil performance of changing one or more of the design parameters could be assessed without having to re-run the simulation for every correction.

Accounting for the coupling between components, design conditions, and the design parameters of individual compo-

nents, are the major obstacles in correcting system performance. In relation to correcting cooling coil performance, the correction procedure was informed by working practice. The rules of thumb employed were effective in making crude corrections, but since the coupling between design parameters was not taken into account, they failed in several examples to fully correct the size of the cooling coil. Future research should address the modeling of parameter coupling, as well as incorporating more advanced "optimal design" methods of correcting performance.

Clearly, the simulation used in any study is going to influence the level of analysis and correction. For instance, a steady-state simulation is going to restrict the analysis of the control system to the supervisory control functions, whereas a dynamic simulation will allow the stability of the local loop control to be assessed. The definition of the changing load on the system will also influence not only the simulation of the control functions, but also performance indicators such as seasonal efficiency. Finally, therefore, any future research program should consider more closely the form of simulation adopted when formulating global rules for analysis and correction.

NOMENCLATURE

<i>A_f</i>	= face area of the coil
<i>A_i</i>	= internal cross-sectional area of the water tubes
<i>C_p</i>	= specific heat capacity of air at constant pressure
<i>g_{ai}</i>	= moisture content of the air entering the coil
Height	= coil height
<i>m_a</i>	= mass flow rate of air
<i>m_w</i>	= actual water mass flow rate through the coil
<i>m_{wmax}</i>	= maximum water flow rate through the coil
<i>m_{wpeak}</i>	= rule of thumb for the maximum water flow rate through the coil (0.042 kg/s · kW [peak duty])
<i>N_{circ}</i>	= number of coil water circuits
<i>N_{row}</i>	= number of coil rows
<i>pb</i>	= proportional band of the controller
<i>Q_t</i>	= peak duty of the coil (kW)
<i>shr</i>	= coil sensible heat ratio (sensible duty/total duty)
<i>sp</i>	= air setpoint temperature
<i>spvol</i>	= specific volume of air
<i>t_{ai}</i>	= air temperature at inlet to the coil
<i>t_{ao}</i>	= air temperature at outlet to the coil
<i>t_{wi}</i>	= water temperature at inlet to the coil
<i>v_f</i>	= air face velocity onto the coil
<i>v_w</i>	= water velocity
Width	= coil width
<i>ρ</i>	= density of water

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DISCUSSION

Jeff Haberl, Department of Mechanical Engineering, Texas A&M University, College Station: Can you comment on your impression of the U.K. HVAC-KBS research and the comparison to U.S. HVAC-KBS research?