DEMONSTRATION OF ESP-r's ADAPTIVE CONVECTION ALGORITHM

Ian Beausoleil-Morrison

CANMET Energy Technology Centre, Natural Resources Canada, Ottawa
(ibeausol@nrcan.gc.ca)

ABSTRACT

A flow responsive algorithm was devised and implemented within the ESP-r simulation program to advance the modelling of internal surface convection. The impact of this method is demonstrated with two case studies. The method is able to resolve the impact that HVAC systems have upon room convective regimes and can substantially affect simulation results. The total annual heating load predictions of an energy efficient house were found to increase by up to 3.3%. The method had an even greater impact on the simulation of a typical office building conditioned with a air-based heating and cooling system. In this case, the method increased the predicted annual heating coil load by 9% and the cooling coil load by 19%.

INTRODUCTION

The convective heat exchange between internal building surfaces (walls, windows, etc.) and indoor air significantly affects a room's energy balance. For example, this mechanism determines the timing and degree to which solar gains absorbed by internal surfaces warm the room air. The common approach for modelling this important heat flow path within dynamic whole-building simulation programs is to employ the so-called *well-stirred* assumption (refer to Figure 1). This treats the room air as uniform and characterizes surface convection heat transfer (q''_{conv}) by a convection coefficient (h_c) and by the temperature difference between the room air and the internal surface.

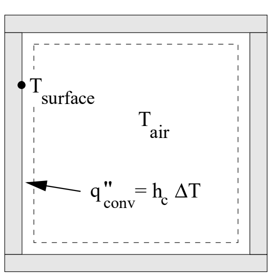

Figure 1: Well-stirred convection model

Convection heat transfer varies from surface to surface in the building, as well as with time, in response to local air flow patterns. Therefore, the calculation of convection coefficients must respond to local flow conditions in a dynamic fashion in order to accurately capture this effect. This contrasts with the simplified treatments commonly employed in building simulation programs: many programs employ time-invariant h_c values or use correlation equations which characterize h_c for a single flow regime (most often buoyancy driven flow).

The significance of the choice of h_c algorithm (made by program developer or user) on simulation results has been well demonstrated (Waters 1980; Irving 1982; Bauman et al 1983; Alamdari et al 1984; Spitler et al 1991; Clarke 1991; Lomas 1996; Fisher and Pedersen 1997; Beausoleil-Morrison and Strachan 1999). Energy prediction sensitivities in the order of 20-40% have been observed. More significantly, in some cases the predicted benefits from design measures were found to be sensitive to the approach used to model internal surface convection.

Clearly more detailed calculation approaches are required for this significant heat transfer path. One solution to address this need has been implemented in the ESP-r simulation program (ESRU 2000). Known as the *adaptive convection algorithm* (ACA), this method responds the calculation of h_c to the configuration and to the time-varying flow conditions.

This paper illustrates the application of the ACA using two case studies: an energy efficient Canadian house and a typical Canadian office building. Simulations are performed using a version of ESP-r modified for the HOT3000 program (see Purdy and Beausoleil-Morrison 2001a for a description). An overview of the ACA is provided in the following section. The case studies, the analysis method, and the simulation results are then described. Conclusions are then drawn and recommendations made for further work.

ADAPTIVE CONVECTION ALGORITHM

A brief description of the ACA is provided in this section. The interested reader is referred to Beausoleil-Morrison (2000; 2001b) for detailed coverage of the ACA's approaches and building blocks.

The ACA is built upon a foundation of 28 h_c correlation equations and employs a series of automated assessments and user prompts during the problem definition stage to appraise conditions in each room.

Each internal surface is attributed with a set of h_c equations appropriate for the flow conditions anticipated over the duration of the simulation. As the simulation progresses, a controller monitors the operational state of HVAC equipment (other control schemes are possible) to assess the flow regime. Based upon this assessment, the controller dynamically assigns (for each surface) an appropriate h_c algorithm from amongst the set attributed at the problem definition stage. One of the ACA's calculation control schemes is illustrated in Figure 2.

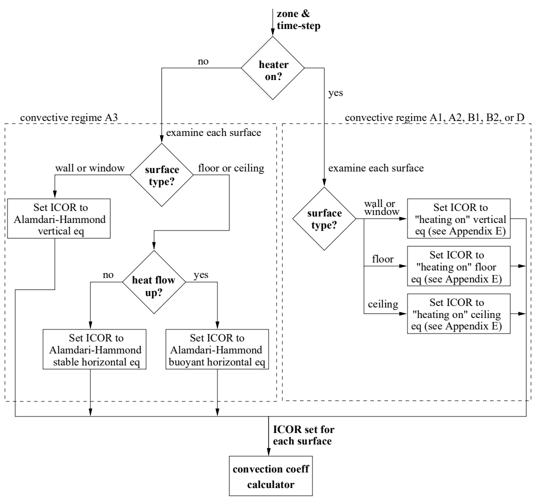

Figure 2: ACA control law for terminal heating

Consider, for example, a room heated by a radiator placed next to an internal wall. When the radiator is on, the temperature difference between the radiator and the surrounding air generates buoyant plumes. These rise and generate a convective regime within the room. The nature of the convective regime is spatially dependent: stronger convective currents are expected nearest the radiator. When the radiator is off, however, no buoyant plumes will form over the radiator. Rather, a weaker convective regime will be established in the room, this generated by buoyancy caused by temperature differences between the room air and internal surfaces. These surface-air temperature differences could be caused by heat transfer through the envelope (e.g. the cold surface of a window) or by sun patches, for example.

The ACA makes use of three h_c correlation equations for the walls to capture these effects. A correlation produced by Khalifa (1989) from experimental data collected in a room-sized test cell heated by a radiator is used for the walls adjacent to the radiator,

$$h_c = 1.98 \cdot \Delta T^{0.32} \tag{1}$$

where ΔT is the temperature difference between the room air and the internal wall surface[1] $\{^oC\}$ and the units of h_c are $\{W/m^2K\}$.

Another Khalifa correlation is used for the other walls in the room,

$$h_c = 2.07 \cdot \Delta T^{0.23} \tag{2}$$

As equations 1 and 2 are only applicable when the radiator is on, a third equation is used when the ACA detects that the radiator is off. This correlation is one recommended by Alamdari and Hammond (1983) for buoyancy driven flow generated by surface-air temperature differences,

$$h_c = \left\{ \left[1.5 \cdot \left(\frac{\Delta T}{H} \right)^{1/4} \right]^6 + \left[1.23 \Delta T^{1/3} \right]^6 \right\}^{1/6} \tag{3}$$

where H is the height of the wall $\{m\}$.

Using the logic illustrated in Figure 2, the ACA toggles between equations 1 to 3 to calculate h_c values for the walls. For a given time-step, the ACA uses equations 1 or 2 to calculate h_c for the walls if it detects that the radiator is supplying heat to the room. And equation 3 is used if the ACA detects that the radiator is off. The same logic (but different equations) are used to calculate h_c for the windows, floors, and ceilings.

ACA calculation control schemes are available to resolve the convective regimes generated by the following HVAC configurations:

- radiators located under windows;
- radiators located elsewhere in the room;
- in-floor heating;
- heated wall panels;
- circulating fan heaters;
- air-based heating and cooling systems.

The ACA is based upon experimentally derived h_c correlations and the method has undergone both analytical and empirical validation tests (Beausoleil-Morrison 2000). The ACA technique is unique to ESP-r. Most simulation programs use a single h_c correlation for all surfaces and do not vary the equation with time. In fact, many programs simply assign a fixed value for h_c. The next sections illustrate the impact the ACA has upon simulation results.

[1] Khalifa chose to regress the data using the average room air temperature, rather than the temperature of the plume rising from the radiator.

RESIDENTIAL CASE STUDY

One of the houses at the Canadian Centre for Housing Technology (CCHT) was selected as the residential case study to demonstrate the ACA. The CCHT (Swinton et al 2001) represents a typical modern energy efficient Canadian house, being airtight, well insulated, and having high performance windows. and being airtight. A model of the CCHT was constructed in ESP-r making use of infiltration and ground contact algorithms added for HOT3000. Purdy and Beausoleil-Morrison (2001a) provide a detailed description of the modelling approaches employed.

Impact of ACA on h_c calculations

Three simulations were performed with the CCHT model to investigate the ACA's impact on h_c calculations. ESP-r's default internal convection treatment was employed in the first simulation. With this, the Alamdari and Hammond (1983) h_c correlations for buoyancy-driven flow are used for all surfaces and at all time-steps of the simulation (a common approach with simulation programs and the approach usually employed by ESP-r users). The ACA was then invoked for the second simulation. All internal surfaces in the house's living space were attributed with convection calculation control data for the case of rooms heated with radiators located under windows[2]. ESP-r's default h_c treatment was retained for the other three zones. The simulation was then repeated using the same weather data and simulation parameters.

This process was repeated for the third simulation but this time the surfaces were attributed with convection calculation control data for the case of rooms heated with radiators which are not located under windows.

No other changes were made to the model between variants. Typically when comparing different heating systems, alterations would be made to the zone control data to specify which nodes interact with the plant components (e.g. a portion of the heat output from a radiator would be convective and thus would inject to the air node while a portion would be radiative and thus would inject to surface nodes). However, all runs presented here assumed the plant injected heat to the zone air-point, this to isolate the impact of the ACA. A 10-minute time-step was used in all simulations.

The h_c values calculated for an east facing window on a typical winter day (February 10) are plotted in Figure 3. This figure compares the h_c values resulting from the three simulations. As can be seen, the ACA produces substantially higher h_c for the majority of the day: from midnight to 7h00; from 11h00 to 19h30; and from 20h30 to midnight. For the case of radiators not located under windows, the h_c values are 25 to 30% more than the default treatment. When the radiators are placed under the windows the values are 40 to 45% greater.

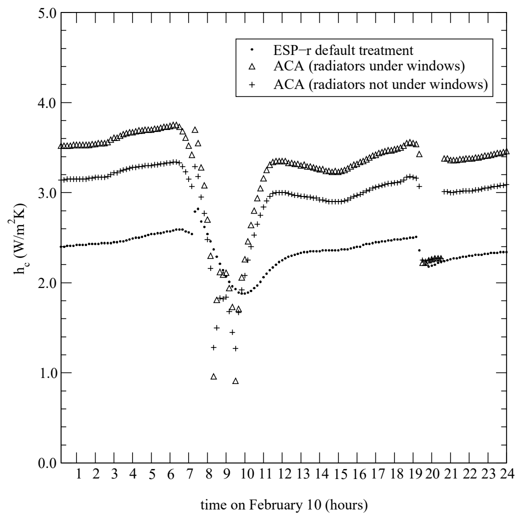

Figure 3: Impact of ACA on h_c calculations

From about 7h30 until 11h00 the h_c values drop substantially in all three simulations. There are significant solar gains to this east facing window during this morning period. This warms the window's internal surface to near the room air temperature. The resulting small surface-air temperature differences produce low h_c values (see equations 1 to 3).

When the nightly thermostat set-back comes into effect the three simulations produce similar h_c values. No heating is supplied for about one hour following the set-back as the house cools to the lower temperature setting (see the period around 20h00 in Figure 3). As explained in the previous section, the ACA toggles to the Alamdari-Hammond correlation when the radiator is off (see Figure 2). Therefore, during this cooling period the ACA employs the same equation as ESP-r's default approach to calculate the window's h_c. This toggling behaviour of the ACA's performance is clearly seen in Figure 3.

These results demonstrate that the ACA has a substantial impact on the calculation of h_c values. The actual impact of these h_c differences on temperature and energy flows is examined in the next section.

Impact of ACA on zone energy balance

ESP-r is based upon a control-volume heat-balance methodology. The building is discretized by representing air volumes, solid-air interfaces, and envelope

[2] The optional window correlations were not used in any of the simulations reported here due to their tendency to overestimate h_c (Beausoleil-Morrison 2000).

components with nodes. An energy balance is written for each node and the resulting set of equations solved to predict nodal temperatures and inter-nodal energy flows. These energy balances are reformed and resolved each time step of the simulation.

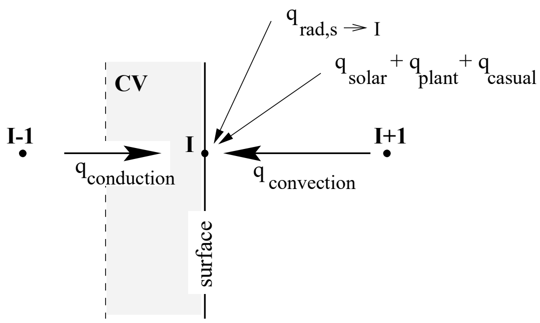

Figure 4: Heat balance at an internal surface

Figure 4 focuses on a node (I) located at an internal surface (e.g. the window considered above). This node's energy balance takes the following form (where CV is the control volume represented by the node),

$$\left\{\begin{matrix} storage\ of \\ heat\ in\ CV \end{matrix}\right\} = \left\{\begin{matrix} net\ conduction \\ into\ CV \end{matrix}\right\} + \left\{\begin{matrix} source\ of\ heat \\ within\ CV \end{matrix}\right\} \qquad (4)$$

$$+ \left\{\begin{matrix} net\ longwave \\ radiation \\ into\ CV \end{matrix}\right\} + \left\{\begin{matrix} net\ convection \\ into\ CV \end{matrix}\right\}$$

The rate of change of the control volume's temperature characterizes the storage term. The source term includes the radiant portion of heat injected from the HVAC system, solar gains, and longwave radiation from sources of heat within the room (e.g. lighting, occupants). The longwave radiation term represents the net heat exchange with the room's other internal surfaces.

The previous section showed how the ACA affects h_c values, and therefore the last term in equation 4. The resulting impact on temperature and energy flow predictions depends upon the importance of convection relative to the other terms in equation 4. To explore this, some of the temperatures predicted in the three simulations were compared. Figure 5 plots the zone's air-point temperature and the internal surface temperatures of the east facing window and a south facing wall. The time period examined is the same as in Figure 3.

The influence of the thermostat's nightly set-back can be clearly seen. For the sake of clarity, only the air-point temperatures predicted with the default convection treatment are shown in the figure. The ACA simulations predicted very similar air-point results, with

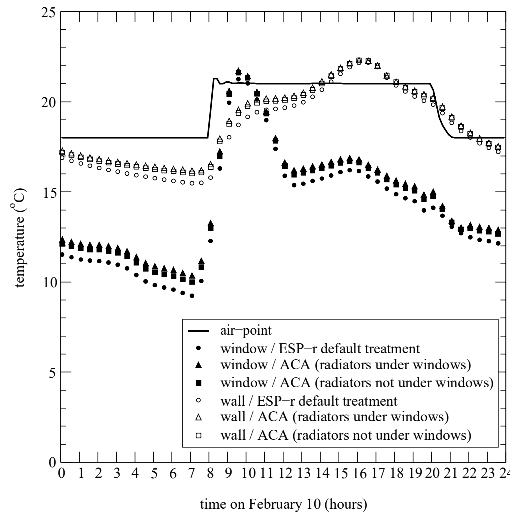

Figure 5: Impact of ACA on T_{air} and T_{surf}

only slight differences observed in the reaction to the nightly set-back.

The ACA had a significant impact on the internal surface temperature predictions, however. As can be seen, the wall and window surfaces are consistently warmer in the ACA simulations. The radiator responds to the zone's energy balance to maintain the set-point temperature. The greater h_c predicted by the ACA therefore results in higher internal surface temperatures, the degree of augmentation depending on the relative strength of the terms in equation 4. In this case, the ACA increases the window's internal surface temperature by up to 1.1^oC and the wall's by up to 0.6^oC. These higher internal surface temperatures consequently increase the heat transferred through the envelope components, this increasing the energy usage of the radiator (the impact on energy will be discussed shortly).

The energy exchange between the room air and the envelope components is also significantly affected by the ACA. Figures 6 and 7 plot the convective heat transfer to the east facing window and the south facing wall[3] (the figures cover the same time period as before). The convection component is more dominant in the window's energy balance (principally due to the wall's high insulation level). As such, the ACA has a greater impact on the window than on the wall. The convection to the window can be as much as 24% higher with the ACA while the convection to the wall

[3] ESP-r's default approach was used to calculate h_c at the *external* surfaces as a function of wind velocity. Simulation results have been shown to be less sensitive to the treatment of external h_c than to internal h_c (Beausoleil-Morrison and Strachan 1999).

can be 12% higher. This effect is clearly seen in the figures as is the significance of the placement of the radiator.

Therefore, the ACA substantially affects the zone energy balances. The impact upon predicted energy consumption is examined in the following section.

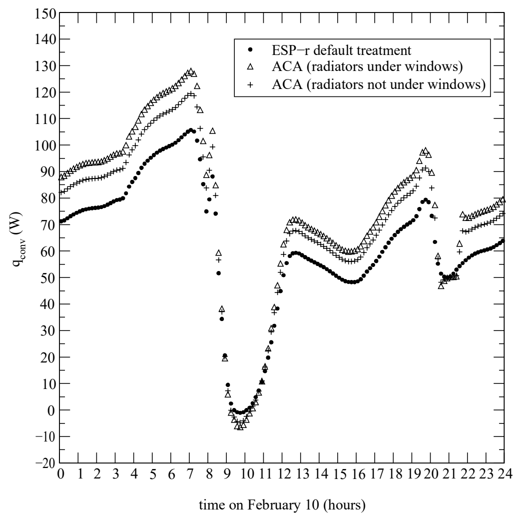

Figure 6: Convection to east facing window

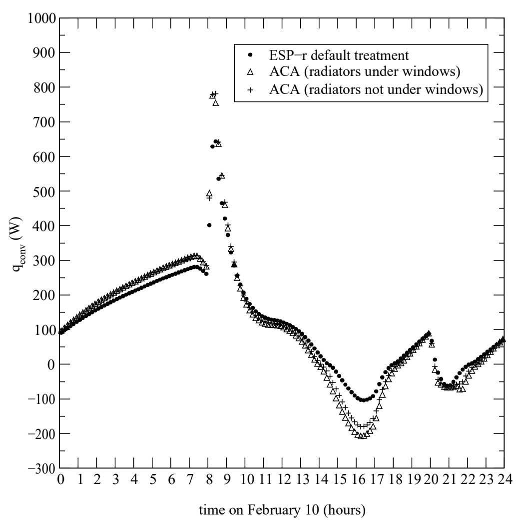

Figure 7: Convection to south facing wall

Impact of ACA on heating loads

An annual simulation was performed with the CCHT model using ESP-r's default convection treatment. This predicted an annual heating load of 50.2 GJ. Six simulations were then performed with the ACA. In each case the internal surfaces of the living space were attributed with convection calculation control data to simulate different heating systems and device placements. The scenarios examined were:

- radiators placed under windows;
- radiators placed by internal walls;
- radiators placed by external walls but not underneath windows;
- in-floor heating;
- hydronic walls panels placed on internal walls;
- forced-air heating system delivering air through registers located under windows[4].

The ACA resulted in greater annual heating load predictions in all scenarios (see Figure 8). Differences ranged from 2.4% to 3.3% of the house's total heating load caused by heat losses through the walls, windows, ceiling, basement, and due to infiltration. This sensitivity is significant. In fact, the CCHT model was found to be less sensitive to a substantial change in the house's internal thermal mass; to neglecting shading by the roof overhang; and to a 10% change in the SHGC of the windows (Purdy and Beausoleil-Morrison 2001b). Additionally, the ACA had a similar impact on annual heating load predictions as the following factors:

- increasing the U-value of the windows by 10%;
- ignoring damper control on the furnace flue;
- changing models for predicting the diffuse solar radiation distribution;
- ignoring shading by neighbouring houses.

As can be seen in Figure 8, the ACA can discriminate the impact that different HVAC systems have upon heating loads. It is important to note that minor alterations to the convection calculation control data can affect these results. Factors such as which walls are adjacent to the radiator, and which surfaces receive the direct stream of the supply air can influence the selection of h_c correlations for each surface.

It is worth noting that the sensitivity of load predictions to h_c modelling is highly dependent upon the building envelope construction. The CCHT is a well insulated building with low U-value windows. The ACA was found to have a much greater impact (up to 16% for the heating scenarios examined here) on the loads predicted for a less insulated building modelled with British weather data (Beausoleil-Morrison 2001b). To further examine this effect two additional simulations of the CCHT were performed. In this case the thermal characteristics of the envelope were derated (2x4 rather than 2x6 construction and standard double-glazed windows). In this case, the ACA simulation with the forced-air heating system produced a

[4] The ACA lacks h_c correlations for this configuration. As such, it was modelled with the closest match, a circulating fan heater.

heating load that was 4.9% greater than the default case. These results demonstrate that simulation results are more sensitive to h_c values is less insulated buildings, when convection plays a more dominate role in the surface energy balances (refer to equation 4).

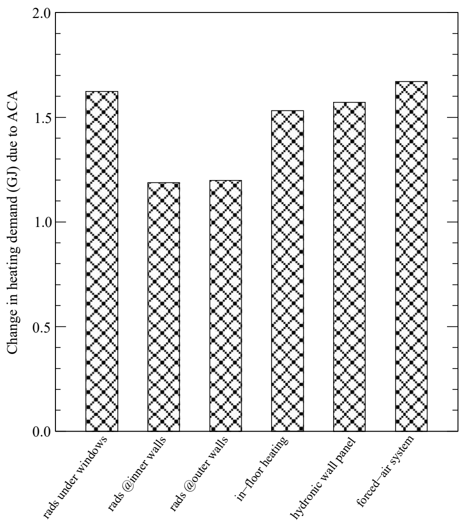

Figure 8: Impact of ACA on annual heating loads

OFFICE BUILDING CASE STUDY

An ESP-r model of a hypothetical shallow-floor-plate office building was created. A single storey was modelled and this was divided into east and west facing zones (150 m^2 floor area per zone). The envelope assemblies, insulation levels, and internal gains are typical of Canadian construction (NRC 1997) and 35% of the external wall area is glazed. Each zone is conditioned with a constant-volume forced-air mechanical system whose supply-air temperature varies from 13°C to 43°C in response to loads. During occupied hours the system delivers 60 L/s of outdoor air to each zone. The building is heated to 22°C, with an 18°C setback during unoccupied hours. The cooling set-point is 24°C but the building is allowed to free float during unoccupied periods in the summer. At 6 ac/h, the HVAC system is adequately sized to meet the peak heating load but cannot satisfy the peak cooling load (Ottawa weather conditions).

Impact of ACA on heating and cooling loads

Two annual simulations—identical except for the treatment of internal convection—were performed to compare ESP-r's default convection treatment with the ACA. In this case, the ACA was configured to employ a set of h_c correlations for mixed flow, in which both forced effects and buoyancy effects are important (Beausoleil-Morrison 2001a). When the HVAC system is supplying air to the zones, the ACA calculates h_c in response to the flow rate and temperature of the air supplied at the diffuser, and in response to the room air and internal surface temperatures. The ACA again toggles to the Alamdari-Hammond correlations when the fan system is shut down.

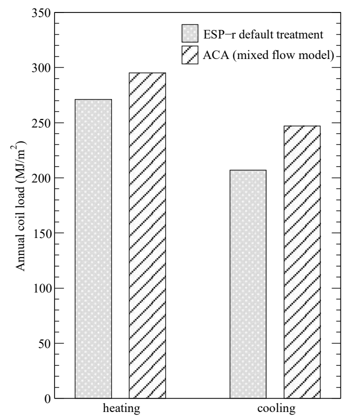

Figure 9: Impact of ACA on annual coil loads

The annual loads (normalized by floor area) placed on the HVAC system's heating and cooling coils are shown in Figure 9. Clearly, the choice of h_c algorithm has a significant impact on the prediction of annual heating and cooling loads (and thus energy consumption). The ACA predicts significantly higher heating and cooling loads (9% and 19% respectively). The cooling loads are more affected by the ACA because ESP-r's default treatment predicts very low h_c during much of the cooling season, this due to low surface-air temperature differences (refer to the functional form of equation 3).

Impact of ACA on assessment of design options

As mentioned, at design conditions the constant volume HVAC system does not meet the peak cooling load. Examination of the zone air-point temperature predictions on days with high cooling loads revealed that comfort conditions could not be maintained. The designer might explore a number of options to address the overheating problem, including:

- increasing the system's cooling capacity by 50% by increasing the air flow rate from 6 to 9 ac/h;
- increasing the cooling capacity by approximately 25% by lowering the minimum supply air temperature from 13°C to 10°C;
- changing to a VAV system with a constant supply temperature of 13°C, a minimum flow of 6 ac/h, and a maximum flow of 9 ac/h, effectively increasing cooling capacity by 50%;

- reducing solar gains by adding window overhangs.
- pre-cooling the building by night purging with 100% outdoor air at 6 ac/h.

Each of these design options was simulated twice: first with ESP-r's default convection treatment and then with the ACA. All measures reduced the peak zone temperatures, with varying degrees of success, and all had an influence on cooling loads. Figure 10 plots the impact of the design changes on the cooling load for the month of July.

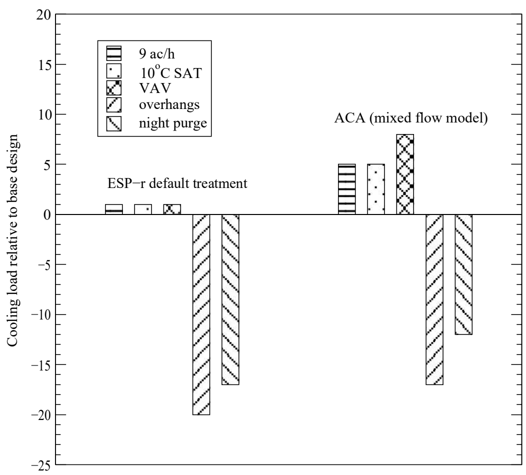

Figure 10: Impact of design options on cooling coil loads for July

The first three design options alter the convective regime: different air flow rates and supply air temperatures result. The ACA is able to respond to these changes. It predicts higher cooling loads (5%, 4%, and 8%, respectively) for the first three design options, a result of the increased cooling capacity *and* increased surface convection. In contrast, ESP-r's default approach is not capable of responding to these changes in the flow regime. Consequently, cooling load predictions are only slightly higher (about 1%) and due entirely to the fact that the cooling system was able to extract more energy because of its higher capacity. In contrast, the default approach predicted greater savings with overhangs and night purging. These measures reduced cooling loads substantially with both convection methods, but the lower h_c produced in the default runs overpredicted the savings.

CONCLUSIONS

There is substantial evidence in the literature to demonstrate the importance of accurately modelling internal surface convection within building simulation programs. Despite this, most programs still employ simplified approaches.

To address this need, a flow responsive method to improve the modelling of internal surface convection has been implemented in ESP-r. This *adaptive convection algorithm* (ACA), employs a series of automated appraisals and user prompts during the problem definition stage to appraise conditions in each room. Each internal surface is attributed with a set of h_c equations appropriate for the flow conditions anticipated over the duration of the simulation. As the simulation progresses, a controller monitors critical simulation variables to assess the flow regime. Based upon this assessment, the controller dynamically assigns (for each surface) an appropriate h_c algorithm from amongst the set attributed at the problem definition stage. The ACA currently supports 28 experimentally derived h_c correlations and has been structured such that new correlations can be easily incorporated when they become available. The method has undergone both analytic and empirical validation tests.

This paper demonstrated the ACA's impact on simulation results using two case studies. In simulations of an energy efficient house, the ACA gave h_c predictions that were up to 45% greater than ESP-r's default approach. These simulations also demonstrated that the ACA's calculations are highly sensitive to subtle changes to the convective regime, such as the placement of radiators in the room. The ACA's h_c calculations were found to have a substantial impact upon internal surface temperature and convective heat flow predictions. Compared to ESP-r's default treatment, the ACA raised the window's internal surface temperature by up to 1.1^oC and the wall's by up to 0.6^oC. Convection heat transfer from the room air to the window was as much as 24% higher with the ACA while the convection to the wall was up be 12% higher. The ACA also lead to greater annual heating load predictions. Results were sensitive to the type and placement of the heating system, and were up to 3.3% of the house's total heating load caused by heat losses through the walls, windows, ceiling, basement, and due to infiltration. The sensitivity of load predictions was found to be highly dependent upon the building envelope construction. In general terms, the lower the envelope's resistance to heat transfer, the greater the impact of the ACA.

The ACA was found to have an even greater impact on the simulation of a typical office conditioned with an air-based HVAC system. In this case, the ACA lead to annual heating and cooling coil loads that were 9% and 19%, respectively, greater than found with ESP-r's default convection treatment. The examination of a number of design measures aimed at mitigating an overheating problem illustrated that the ACA is able to respond to changes in the flow regime resulting from mechanical system alterations, but ESP-r's buoyancy-only default approach cannot. As a result, it was found that the ACA could influence design decisions drawn from a simulation-based analysis.

The ACA draws heavily upon the experimental work of others who provide h_c correlations for various convective regimes. Approaches were found to characterize most of the principle convective regimes, however further research in this field is required. Clearly the operation and placement of HVAC equipment has a profound impact on internal surface convection. Many systems have yet to be investigated. For example, for the residential results reported here an h_c correlation for a circulating fan heater was used to approximate the convective regime generated by a forced-air furnace. Given the importance of this heating system in residential applications, the accuracy of this approximation should be tested and, potentially, new h_c correlations developed for forced-air furnaces. Finally, further validation of the ACA is warranted. This will require the collection of high quality empirical data sets.

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