Seventh International IBPSA Conference
Rio de Janeiro, Brazil
August 13-15, 2001

FLOW RESPONSIVE MODELLING OF INTERNAL SURFACE CONVECTION

Ian Beausoleil-Morrison

CANMET Energy Technology Centre, Natural Resources Canada, Ottawa Canada
(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. Empirical methods were extracted from the literature and a new method for characterizing mixed flow was created to provide the algorithm with a basis of 28 convection coefficient correlations. Collectively these methods can calculate convection coefficients for most flows of practical interest. Working with this suite of correlations, the algorithm dynamically controls the modelling of convection by assigning appropriate equations to each internal surface each time-step of the simulation.

INTRODUCTION

The convective heat exchange between internal building surfaces (walls, windows, etc.) and indoor air significantly affects a room's energy balance. The common approach for modelling this 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.

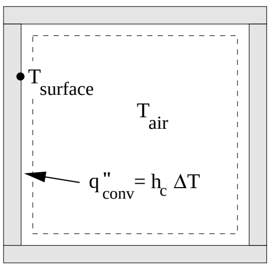

Figure 1: Well-stirred convection model

Convection heat transfer varies from surface to surface in the building, as well as with time, in response to local air flow patterns. 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: the use of time-invariant h_c values or correlation equations which characterize h_c for a single flow regime are common.

Numerous researchers have examined the sensitivity of simulation predictions to the modelling of internal convection (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; Beausoleil-Morrison 2001). They have demonstrated that predictions of energy demand and consumption can be strongly influenced by the choice (made by program developer or user) of h_c algorithm. 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 the need is put forward in this paper. It is referred to as the *adaptive convection algorithm* (ACA). Two building blocks of the ACA are first described: a pragmatic and extensible scheme for broadly classifying the principle convective regimes encountered within buildings; and a suite of methods for calculating h_c values for these convective regimes. Following this, the two-step procedure that was devised and implemented into the ESP-r simulation program (ESRU 2000) to respond the calculation of h_c to evolving flow regimes is described. The results of simulations performed with the ACA are then presented. Finally, conclusions are drawn and recommendations made for further work.

THE PRINCIPLE CONVECTIVE REGIMES FOUND IN BUILDINGS

It would be an impossible task to develop and implement models for predicting h_c for all possible flow regimes encountered within buildings. Even the presence and location of furniture, and the movement and metabolic functioning of occupants alters indoor air flow patterns, and thus convective heat transfer at internal surfaces. Given this, the pragmatic way forward is to broadly classify the air flows encountered within buildings and to establish methods for resolving their influence on internal convection.

The forces that drive indoor air flow can be described as either mechanical or buoyant. Mechanical forces are generally caused by fans or by wind

convective regime	driving force	cause of driving force
A	Buoyant	Surface-to-air temperature difference, caused by one of the following: • heat transfer through the external envelope; • solar insolation to walls or floor (i.e. sun patch); • in-floor heating; • chilled ceiling panels; • heated walls (e.g. hydronic wall panels).
B	Buoyant	Heating device (e.g. radiator, stove) located within room.
C	Mechanical	Air handling system (central or zonal) delivering supply of heated or cooled air to room through ceiling, floor, or wall-mounted diffusers. Exhaust air mechanically extracted or exfiltrated.
D	Mechanical	Heating or cooling device with circulating fan. No intentional supply or extract of air from room.
E	Mixed flow (mechanical and buoyant)	Mechanical forces caused by air handling system (central or zonal) delivering supply of heated or cooled air to room through ceiling, floor, or wall-mounted diffusers. Buoyant forces caused by surface-to-air temperature differences (as described above).

Table 1: Classifying the principle convective regimes

entering through openings. Fans can be located within the room and circulate air from a heating or cooling device. Or, they can be located in an air-handling unit that supplies and extracts air to the room for ventilating, heating, or cooling purposes. Buoyant forces can result from heat sources located within the room (radiators, occupants, office equipment, etc.) or from surface-to-air temperature differences. The surface-to-air temperature differences can be caused by heat transfer through the building fabric (e.g. the cold surface of a window), solar insolation, or fabric-embedded conditioning devices (e.g. in-floor heating, chilled ceiling panels). In some cases, both mechanical and buoyant forces can be significant drivers of room air motion.

Further subdivision is possible. For example, in the case of buoyancy-driven flow resulting from the presence of a wood stove, whether the stove is located in the middle of the room, or next to an external window, will have an affect of the room's air flow pattern. In the latter case, the warm plumes rising from the stove will be cooled by heat transfer through the window, causing a competition in the buoyant effects. Similarly, in the case of mechanically driven flows, the location of the supply air diffuser and the extract will influence which walls experience wall jet flow and which experience impinging flow. Clearly some factors have a greater influence than others. Whether the room is mechanically ventilated or not has a more profound influence on the convective regime than does the location of diffusers and extracts.

A pragmatic approach was established for calculating convection coefficients for this research. This classifies the indoor air flow into one of five categories according to the type and cause of the driving force. This scheme is presented in Table 1. A scheme based upon fundamental considerations could have been devised, however this pragmatic approach best fits the building simulation process.

Convective regimes A and B describe situations where the flow is caused principally by buoyant forces. In the former case, the buoyancy is caused by surface-to-air temperature differences resulting from heat transfer through the fabric, a sun patch, or a embedded conditioning device. The latter describes a substantially different buoyancy induced flow regime, this caused by the presence of a heating device located within the room. Flows which are principally mechanically driven have been broken into two categories: regime C considers HVAC systems that deliver and extract air to the room, while regime D is for sealed rooms with circulating fans. Finally, convective regime E covers the case of mixed flow where both mechanical and buoyant forces are present and significant.

Given this classification scheme, the task becomes one of selecting methods for calculating convection coefficients for each of these five regimes, the subject of the next section.

A SUITE OF h_c METHODS

The literature was extensively surveyed for methods appropriate for calculating convection coefficients for the five flow regimes. Many methods exist, but none is universal. Some are general in nature while the applicability of others is restricted to specific building geometries and HVAC systems. Most are simple in form, often regressions of empirical data which give h_c as a function of room-air and surface temperatures. Many of the methods were rejected for the current research because their applicability is too restricted, or they are of limited appeal in building modelling.

Based upon this review, four methods were selected to address the buoyant (A and B) and mechanical (C and D) flow regimes listed in Table 1. No appropriate method could be found for the mixed flow regime (E). Consequently, a new approach was devised. These five methods, which produced a suite of 28 h_c correlations for ESP-r, are briefly described in this section. The interested reader is referred to Beausoleil-Morrison (2000) for a more detailed description of the methods as well as a general review of the literature.

The Alamdari and Hammond method

The Alamdari-Hammond (1983) method was one of the first to be developed specifically for building applications. Rather than conducting new experiments, they drew upon data reported in the literature to develop their correlations. Separate correlations are given for: vertical surfaces; stably-stratified horizontal surfaces (e.g. warm air above a cool floor); and buoyant flow from horizontal surfaces (e.g. cool air above a warm floor). The correlations span the full range of temperatures and dimensions relevant to building applications.

This method is applicable for purely buoyant flow, and only where buoyancy is caused by a temperature difference between a surface and the surrounding room air. They are not appropriate for cases where buoyancy is generated by a heating device, such as a radiator. Consequently, the applicability of this method is restricted to convective regime A (all causes of the driving force).

The Khalifa method

Khalifa (1989) conducted experiments in a room-sized test cell to produce correlations specific to internal convection within buildings. The test cell's configuration was varied and experiments repeated to assess a number of common convection regimes. Convective heat transfer at internal surfaces was not measured directly, but rather h_c was derived from temperature and heat input measurements. It is important to note that radiant exchange was neglected in this derivation. As such, it is believed that Khalifa's results tend to overestimate h_c. Although there are insufficient data available to determine the degree of overestimation, the errors would be greatest in the cases with large temperature differences between surfaces (such as a hot radiator facing a cold window). Notwithstanding, Khalifa's work represents a significant contribution, as he provides h_c data for room configurations not analyzed by others.

Eight of Khalifa's correlations were included in ESP-r. These include correlations for walls, windows, and ceilings. No correlations are given for floors, because Khalifa did not derive h_c values for the floor. Rooms heater by radiators, warm walls, warm floors, and circulating fan heaters can be characterized. Two radiator placements are considered: underneath a window or located elsewhere. In addition, the selection of the h_c equation for walls is sensitive to the placement of the heating device. For instance, when the room is heated by a circulating fan heater, one equation is used to calculate h_c for the wall with impinging flow, whereas another equation is used for all other walls.

In terms of the convection classification scheme, the eight Khalifa correlations implemented into ESP-r address convective regimes A (all sources of the driving force but chilled ceiling panels), B, and D.

The Awbi and Hatton method

Awbi and Hatton (1999) performed a series of experiments to characterize natural convection from heated room surfaces. Like Khalifa, they derived the convective heat transfer from temperature and heat input measurements (although in this case radiation was not neglected).

Only a portion of the wall or floor surface was heated in some of the experiments. This simulated a solar patch, for example, where solar insolation strikes only part of a wall or floor. They found that these data could be represented with a general equation if h_c was evaluated with the hydraulic diameter of the entire surface. In other words, the scale effect of the convection is a function of the enclosure size, and not of the size of the heated area.

The Awbi-Hatton h_c correlations for heated walls and heated floors were implemented into ESP-r. These are useful for characterizing convective regime A (all but the chilled ceilings). However, it is important to note that these equations apply only to the heated surface. For example, the floor of a room conditioned with an in-floor heating system can be characterized with the Awbi-Hatton method, but the walls cannot (these are cooled surfaces).

The Fisher method

Fisher (1995) performed a series of experiments to characterize h_c at the internal surfaces of rooms for forced convection regimes. Convection coefficients were derived using the same approach as Awbi-Hatton (radiation was considered). The experiments spanned a range of air flows and inlet temperatures.

Fisher's correlations for rooms with ceiling-mounted and wall-mounted supply air diffusers were implemented into ESP-r. Both sets of correlations are strictly applicable for isothermal rooms, wherein buoyancy forces caused by surface-to-air temperature differences are negligible. As such, they can characterize convective regime C. As these correlations express h_c as a function of the flow rate and temperature of the air supplied to the room, they are structurally different than those of Alamdari-

Hammond, Khalifa, and Awbi-Hatton: these operate on surface and air temperatures. To address this, a scaling technique was developed and an idealized HVAC model was included in ESP-r to support the Fisher correlations.

A new method for mixed flow

The above four methods can characterize convection coefficients for the buoyancy and mechanical regimes listed in Table 1 (i.e. regimes A through D). However, no suitable method was found in the literature for resolving mixed flow (regime E) in which both mechanical and buoyancy forces are important. Consequently, a new method was developed that blends the Alamdari-Hammond and Fisher approaches (refer to Beausoleil-Morrison 2001 for the equations and their derivation).

The mixed flow model is applicable for mechanically ventilated rooms which are heated or cooled with air supplied through ceiling diffusers. Because one of its building blocks is the Alamdari-Hammond method, it is restricted to cases where buoyancy is caused by a temperature difference between a surface and the surrounding room air. It would be trivial to extend the mixed flow model to overcome these restrictions since, in principle, any of the previously outlined forced and buoyant methods could be blended. So, for example, using this technique one of Khalifa's equations could be blended with one of Fisher's correlations to produce a method for resolving mechanically ventilated rooms with reheating devices located underneath windows.

THE ADAPTIVE CONVECTION ALGORITHM

The previous section described how ESP-r was populated with 28 h_c equations. Because each equation has limited applicability and because convection regimes vary throughout a simulation, this is not sufficient in itself to accurately characterize convection. It is also necessary to assign an appropriate h_c equation to each internal surface at each time-step of the simulation, and to adapt this selection to the prevailing flow conditions.

Therefore, the ACA was devised with the ability to interrogate the configuration and to chose from amongst the suite of h_c correlations. It demands only minimal data input from the simulationist, and is broken into two primary steps (described below):

1) The configuration is appraised prior to commencing the time-step simulation. Each internal surface is attributed with a set of h_c algorithms appropriate for the flow regimes anticipated over the duration of the simulation.

2) As the simulation progresses, a controller monitors critical simulation variables to assess the flow regime. Based upon this assessment, it dynamically assigns (for each surface) an appropriate h_c algorithm from amongst the set attributed in step 1.

STEP 1: ATTRIBUTING SURFACES

The ACA appraises the building during the problem definition stage to determine which h_c methods are appropriate for the prevailing conditions in each room. This is accomplished through a series of user prompts and automated appraisals which are performed on a zone-by-zone basis. A pragmatic approach was devised to minimize data entry and detail specification.

Selecting h_c correlations for the room

Conditions in each zone are first matched to one of the five principle convective regimes listed in Table 1. Where sufficient h_c methods are available, a second level of questioning is used to sub-classify the flow regime (illustrated in Figure 2). For instance, h_c algorithms exist to discriminate between two B regimes: one generated by a heating device located under a window (called B1), and another generated by a heating device located elsewhere in the room (B2). The suite of 28 h_c correlations enabled a total of nine unique convective classifications.

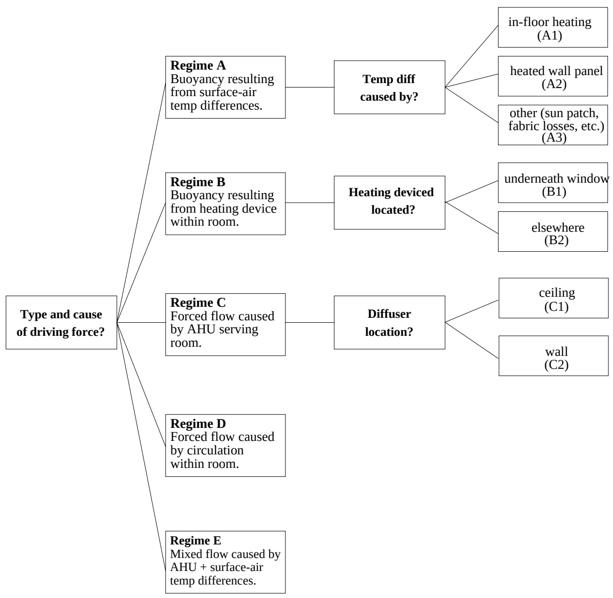

Figure 2: User prompts for appraising flow regime

The assignment of h_c methods for these nine convective classifications was based on applicability assessments of the 28 h_c equations (the full details are presented in Beausoleil-Morrison 2000). This scheme builds upon the synergies between methods. The treatment of heated wall panels (regime A2) is a case in point. The Awbi-Hatton heated wall equation is suitable for the heated wall surface, but not for the other surfaces in the room. One of Khalifa's equations is applicable for rooms with heated wall panels, but only for the wall and window surfaces which are not heated. Similarly, another of Khalifa's equations can resolve the ceiling. As neither Khalifa nor Awbi-Hatton supply an equation for the floor in this case, Alamdari-Hammond's equation for stably stratified horizontal surfaces is used to complete the characterization of the room.

All 28 h_c correlations are utilized by this scheme. Although most flows of practical interest can be modelled, there is much potential for refinement. When additional h_c calculation methods become available the convective regimes can be further subclassified and the scope broadened without altering the structure.

Assigning h_c correlations to surfaces

Once a set of h_c methods has been selected for the room's convective regime, the algorithm then assigns appropriate equations to each internal surface. This is accomplished by examining surface orientation and type (wall, window, floor, ceiling). The algorithm operates on standard geometrical and attribution data which has already been defined, and as such requires minimal input from the user. Additional questions are posed only in cases where decisions cannot be resolved without further user intervention. This is necessary when the selection of h_c methods hinges upon details which are not required in the standard geometrical model, such as: whether the jet from a circulating fan strikes a wall; or whether the heating device is adjacent to a wall.

Primary and secondary convective regimes

The above logic assigns h_c correlations to each surface for the room's primary convective regime. However, as most of the convective regimes (all but A3) are driven by the operation of HVAC equipment, it would be inappropriate to use these h_c methods at all time-steps of the simulation. For a mechanically ventilated room, for example, the mixed flow method is appropriate for calculating h_c values at the ceiling when the system is delivering air to the room. But when the system is shut off at night, convection to the ceiling is not governed by the fan, but rather by buoyancy caused by surface-to-air temperature differences. Therefore, an additional (in some cases two) equation is assigned to each surface, this to calculate the convection coefficient for the room's secondary convective regime (i.e. when the HVAC equipment is not operating).

For the purposes of demonstrating this approach, it is assumed that the secondary convective regime is classification A3, flow driven by surface-to-air temperature differences. It would be conceptually simple to extend the approach to consider more complex scenarios, including the possibility of tertiary flow regimes. For example, a mechanically ventilated room may use a baseboard heater to maintain the setback temperature when the air-handling system is shut off at night. In this case, the primary regime could be E (fan operating), the secondary regime B1 (fan off, but baseboard operating), and the tertiary regime A3 (fan and baseboard off).

Convection calculation control data

Once this information is collected (the process only requires a few seconds of the user's time per zone), each internal surface is attributed with a set of h_c correlations to characterize the primary and secondary convective regimes. A convection calculation control law is also assigned to each surface. This instructs the simulator on how to toggle between the h_c correlations during the time-step simulation, a concept that is treated below.

Example of attributing surfaces

The process is best illustrated with a simple example. Consider a model of a test room shown in Figure 3. The user must make only two menu selections to specify that the room is heated by a radiator located underneath the window. There are four h_c equations that can characterize the room's primary convective regime and three that can characterize the secondary convective regime.

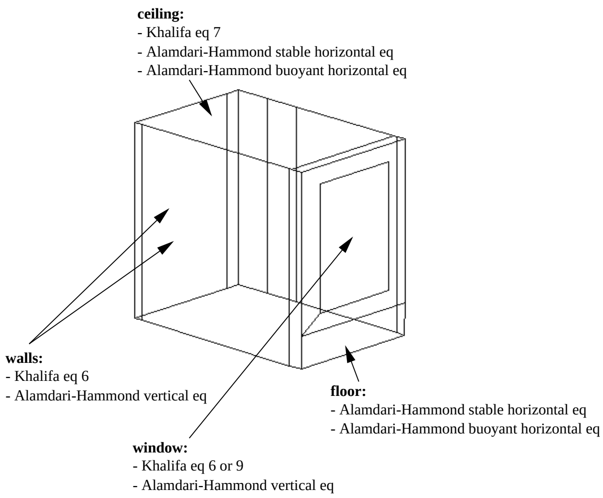

Figure 3: Attributing surfaces with h_c correlations

The geometry is then scanned to make the final attribution of h_c methods to surfaces. For example, three equations are assigned to the ceiling: one of Khalifa's equations for when the heater is on, and the two Alamdari-Hammond horizontal equations. Both Alamdari-Hammond equations are required, as flow under the ceiling may be buoyant or stably stratified, depending upon the air and surface temperatures.

STEP 2: DYNAMIC CONTROL

As discuss above, each surface is attributed with a set of h_c correlations and a control law prior to commencing the time-step simulation. Governed by the control law, the ACA toggles between the set of correlations during the simulation in response to the prevailing flow regime. This process is performed on a surface-by-surface basis each time-step of the simulation.

Convection calculation control laws

Two control laws were implemented to demonstrate this approach. Both adapt the convection calculations in response to the operational state of HVAC equipment. The first is applicable for terminal heating devices (this could be a heated wall panel, in-floor heating, a circulating fan heater, or a radiator) and the second for air-based heating and cooling systems.

Figure 4 illustrates the control logic applied for the first control law. The controller is called once per zone each time-step of the simulation. It first determines whether the terminal device is supplying heat to the room (based on the simulation results from the previous time-step). If the device is heating the room, the h_c values are calculated using the correlations for the primary convection regime. And if the terminal device is not heating the room, the correlations for the secondary convection regime are used. When considering horizontal surfaces for the secondary convective regime, a test is performed (using the air-point and surface temperatures) prior to selecting the h_c correlation to determine whether the flow is stably stratified or buoyant.

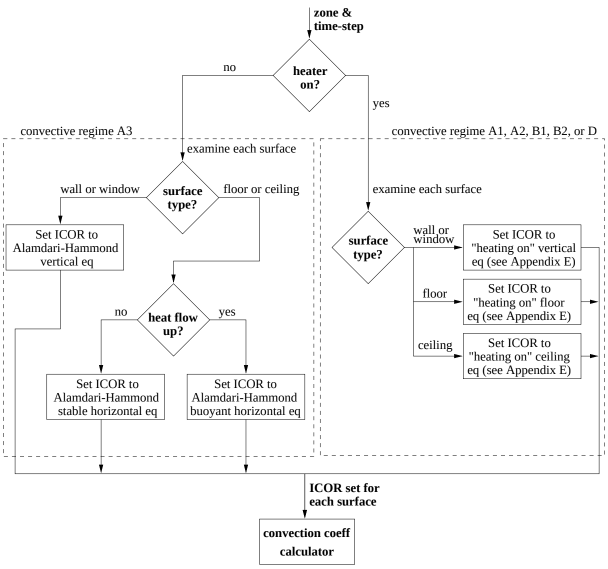

Figure 4: ACA control law for terminal heating

Example of dynamic control

An application of the air-based HVAC system control law is demonstrated in Figure 5. The room is mechanically ventilated from 5h00 to 20h00 and is allowed to free float during unoccupied periods. The mixed flow model is employed. Up until 5h00, the dynamic controller senses that the system is off, and thus employs the Alamdari-Hammond correlations. When the system's fan switches on at 5h00 the dynamic controller switches to the mixed flow model. The idealized HVAC model determines the flow rate and temperature of air supplied to the room, and the h_c calculator applies the mixed flow equations to establish the convection coefficients for the zone matrix. The figure shows how dramatically surface convection at the ceiling increases at 5h00. When the fan shuts off at 20h00, the dynamic controller switches to convective regime A3. At first it determines that flow under the ceiling is buoyant (the ceiling is colder than the room air so buoyant plumes form), but shortly thereafter stably stratified conditions develop.

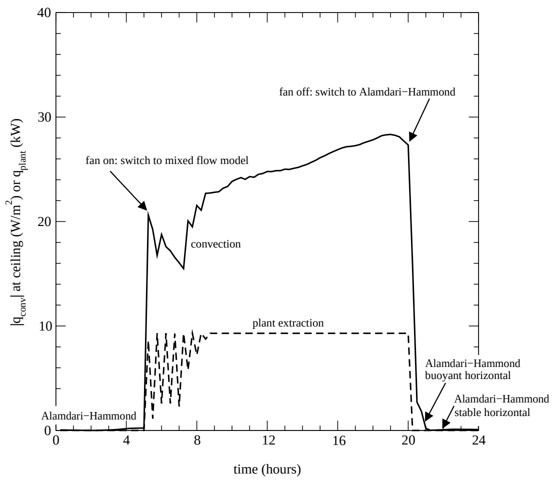

Figure 5 Example of dynamic control

Extensibility

The general principle of the dynamic controller is simple: a simulation variable that governs the convective regime is sensed; a decision on which convective regime prevails is made; appropriate h_c correlations are selected; and the h_c values calculated. This approach has been demonstrated for terminal heating devices and for air-based HVAC systems, but the same logic could be applied in a host of other ways to extend the applicability of the ACA.

As an example, consider a building with a hybrid ventilation system. On days with moderate cooling loads, the cooling equipment and forced-air distribution system are shut off and the building is cooled naturally by ventilation through openable windows. A network air flow model could be established to simulate the opening and closing of windows, the natural ventilation, and the operation of the cooling equipment and forced-air system.

A control law could be created to allow the ACA to sense the network air flow connections representing the windows. If the windows were open, the controller could select an h_c calculation approach for rooms ventilated through windows. And when it sensed the windows were closed and the cooling system was on, the controller could calculate h_c using the mixed flow model.

THE IMPACT OF THE ACA

The ACA can have a profound impact upon simulation results. This is easily demonstrated using an ESP-r model of a simple building. The building (illustrated in Figure 6) is divided into three zones: an office, a reception, and a roof space. The office and reception are heated to 20°C during occupied periods, and allowed to free float during evenings and weekends. The roof is unconditioned.

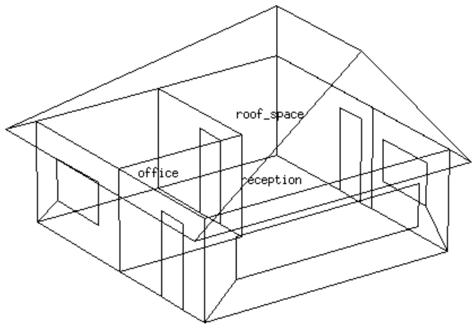

Figure 6: Model for demonstrating the ACA

A simulation was performed with this model for the month of February using 30-minute time-steps. Glasgow weather data was employed in the analysis. The simulation was performed using ESP-r's default internal convection treatment: convection coefficients at all surfaces were calculated with the Alamdari-Hammond correlations at all time-steps of the simulation. It is interesting to note that this treatment—calculating h_c using buoyancy-driven correlations—is the approach employed by many popular simulation programs.

The ACA was then invoked. All internal surfaces in the office and reception were attributed with convection calculation control data for the case of rooms heated with radiators located under windows (regime B1). Khalifa's window correlations were not used in this case due to their tendency to overpredict h_c (as discussed earlier). The simulation was then repeated using the same weather data and simulation parameters. In this case, the ACA dynamically selected the h_c correlations for each surface in response to the operational state of the heating system.

This process was repeated four more times. In each case a different convective regime was assessed by the ACA. The cases examined were: radiators located at internal walls (regime B2); circulating fan heaters (regime D); a constant-volume variable-temperature (CVVT) system delivering heated air at 6 ac/h through ceiling diffusers (regime E); and hydronic wall panels (regime A2).

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 node within the fabric would receive the plant injection in the case of in-floor heating). However, all runs presented here assumed the plant injected heat to the zone air-point, this to isolate the impact of the ACA.

The results of these six simulations are compared in Figure 7. In each case, the ACA resulted in a significant increase (12% to 27%) in the heating load compared to ESP-r's default treatment. As the figure shows, even the location of the radiator within the rooms has a significant impact (5%). As expected, the two air-based systems augment the heat losses by a significant margin (16% and 27%). 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 circulating fan influence the selection of h_c correlations for each surface.

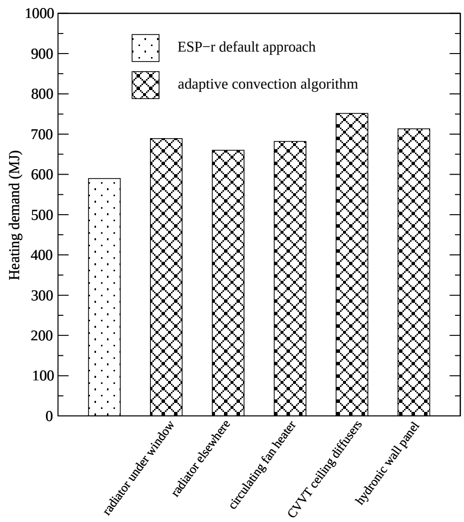

Figure 7: Impact of ACA on heating load

CONCLUSIONS AND RECOMMENDATIONS

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.

A flow responsive method to improve the modelling of internal surface convection was put forward in this paper. Known as the *adaptive convection algorithm* (ACA), it 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. At the basis of this flow responsive method is a scheme for broadly classifying the principle convective regimes encountered within buildings and a suite of 28 h_c correlation equations.

A simple example was used to demonstrate the significant impact that the ACA can have upon simulation results. It is important to note that the process of attributing surfaces with the ACA required only seconds per zone using the facility provided in ESP-r's user interface. Given this and the earlier evidence on the significance of modelling internal surface convection, simulation users should give due consideration before accepting program defaults for internal surface convection coefficients.

Two control laws were implemented to demonstrate the dynamic selection of convection correlations. Both adapt the convection calculations in response to the operational state of HVAC equipment. It would be interesting to extend this approach to control the calculations based on the sensed condition of other simulation variables, such as the state of a network air flow connection.

This work has drawn 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, no suitable method exists to characterize convection generated by forced-air heating systems that deliver air through floor-mounted diffusers located near windows (a common heating system in low-rise housing). Methods appropriate for displacement ventilation, induction units, and other air-based HVAC systems would also be welcomed. As well, new experimental approaches or alternate techniques to derive h_c values from primary measurements may be required to deliver highly accurate h_c data under realistic operating conditions.

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