AIM-2 Implementation into ESP-r

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This document describes in broad terms how the AIM-2 air infiltration model was incorporated into ESP-r's *bps* simulator.

External documentation

The implementation AIM-2 into *bps* is based heavily upon the model description provided by Walker and Wilson (1990). Information and data was also extracted from the HOT2000 version 8.5 bin model source code and the documentation of Bradely (1993). Additional material was also extracted from the following references: Kiel and Wilson (1987); Lew (1993); Wieringa (1986); Wilson and Walker (1990); Wray (1987).

During this work many questions arose regarding the most appropriate strategies to employ to incorporate the AIM-2 model into *bps*. Much of the thinking behind these points which affected the implementation are recorded in e-mail exchanges with Brian Bradley and David Wilson. These e-mails are stored in Microsoft Outlook format within a Winzip file which is located in the same directory as this documentation. This same Winzip file contains e-mail correspondence with Julia Purdy and Iain MacDonald concerning the testing and validation of the implementation. Finally, this document contains three appendices. Each of these contains derivations of equations which are employed in the subroutines incorporated into *bps*. Annotations within the source code refer to specific equations from these appendices.

General methodology

The AIM-2 model is used to calculate the total outdoor air flow rate to the house resulting from the combined effect of natural infiltration and unbalanced mechanical ventilation. These calculations are performed once each time-step of the *bps* simulation and are initiated from the standard *bps* subroutine which calculates the conductances caused by infiltration and inter-zone air flow.

The AIM-2 model predicts the total air flow rate to the house. This total air flow rate is then apportioned to individual zones within the model. These air flows are then converted to conductances between the indoor and outdoor air temperature. These conductances are then absorbed into *bps*'s standard zone energy balances, which are solved in the usual manner to predict nodal temperatures and inter-nodal energy flows.

A detailed description on how each aspect of this methodology is implemented is described with annotations within the relevant subroutines.

Source code structure

Twenty-six subroutines were created to implement the AIM-2 model and three existing *bps* subroutines were modified. Modifications to existing *bps* subroutines were kept to an absolute minimum to simplify merging the AIM-2 model into subsequent ESP-r releases.

The program flow is illustrated in the flowchart which is located in the same directory as this documentation. The 26 new subroutines are contained within two source files. *cetc/aim2_pretimestep.F* contains all the subroutines which are executed prior to *bps* commencing its time-step simulation of the building while *cetc/aim2_timestep.F* contains all the subroutines which are executed within the time-step loop. The function of each of the 26 new subroutines is briefly described in Table 1. Detailed information is contained in code annotations within each subroutine. These annotations serve as the main source of documentation on the implementation details.

The data describing the house's infiltration regime is contained within the *.aim* file. These data are assigned to variables within subroutine AIM2_READIN and placed within MODULE AIM2_INPUT_DATA. A second MODULE, called AIM2_CALC_DATA holds data which result from the calculations.

Testing and validation

Unit testing was performed on each subroutine to ensure that it flows and responds correctly to data inputs. Various input data combinations were passed to each subroutine and its outputs were compared with hand calculations. Program flow and outputs were examined using the Sun Workshop graphical debugger.

Integration testing was performed on the completed model to ensure that the conductances returned by subroutine AIM2_CONTROL were accurately reflected in ESP-r's zonal energy balances.

Additionally, intermediate and final results produced by the AIM-2 model as implemented in *bps* were compared with results produced by an Excel spreadsheet implementation of the AIM-2 model.

The above testing confirmed that the *bps* implementation accurately reproduces the AIM-2 algorithm and that it correctly interacts with ESP-r's zonal energy balance method. Subsequent testing will compare the *bps* infiltration predictions against those from the HOT2000 version 8.5 bin model.

References

Bradley B. (1993), Implementation of the AIM-2 Infiltration Model in HOT2000, Unies Contract Report to NRCan.

Kiel D.E. and Wilson D.J. (1987), 'Influence of Natural Infiltration on Total Building Ventilation Dominated by Strong Fan Exhaust', *ASHRAE Transactions* 93(2).

Lew L., Evaluation of AIM-2, EMR, Apr 23/93.

Walker I.S. and Wilson D.J. (1990), The Alberta Air Infiltration Model: AIM-2, University of Alberta Dept of Mech Eng, Report 71.

Wieringa, J. (1986), ‘Roughness-dependent Geographical Interpolation of surface wind speed averages’, *Quart. J. R. Met. Soc*, 112, 867-889.

Wilson D.J. and Walker I.S. (1990), ‘Combining Air Infiltration and Exhaust Ventilation’, Indoor Air ’90, *Proc 5th Int Conf on Indoor Air Quality and Climate*, Toronto Canada, 467-472.

Wray C. (1997), Letter to Brian Bradley dated March 17.

cetc/aim2_pretimestep.F subroutines	
AIM2_READIN	Reads the data contained in the .aim file.
AIM2_SETVARS	Controls calc of time-invariant data for AIM-2 model.
AIM2_HOUSE_VOLUME	Calculates house volume.
AIM2_FLUEHGT	Sets height of flue.
AIM2_LEAKDIST	Sets leakage distribution fractions.
AIM2_SETJ	Determines foundation type (necessary to look up leakage coeffs).
AIM2_COandN	Calculates fabric leakage coefficient and flow exponent.
AIM2_flue_size	Sets effective opening size of furnace flue.
AIM2_shelter_wall_flue	Sets wall and flue shelter coefficients.
AIM2_wind_correct	Calculates wind speed correction factor.
cetc/aim2_timestep.F subroutines	
AIM2_CONTROL	Controls the time-step AIM-2 calculations.
AIM2_FLUELEAK	Calculates flue flow coefficient.
AIM2_C_R_X_Y	Calculates total leakage coefficient and leakage distribution parameters.
AIM2_stack_flowF	Calculates the stack flow factor.
AIM2_stack_pressure	Calculates the stack effect reference pressure.
AIM2_stack_infil	Calculates the infiltration air flow induced by the stack effect.
AIM2_wind_flowF	Calculates the wind flow factor.
AIM2_wind_shelter	Calculates the wind local wind shelter coefficient.
AIM2_wind_pressure	Calculates the wind effect reference pressure.
AIM2_wind_infil	Calculates the infiltration air flow induced by the wind effect.
AIM2_stack_plus_wind	Calculates the infiltration air flow induced by both stack and wind effects.
AIM2_mechanical	Calculates the unbalanced mechanical ventilation rate in the house
AIM2_comb_nat_mech	Calculates net air flow rate from outdoors caused by combined influence of natural infiltration and unbalanced mechanical ventilation.
AIM2_sumover_DT	Calculates average air flow rate from outdoors over time-step when separate calculations are performed for furnace on and off cycles.
AIM2_split2zones	Apportions infiltration to individual zones in model.
AIM2_airflow_to_conduct	Expresses infiltration air flow rate in terms of a conductance between indoor-outdoor temperature difference.

Table 1

AIM-2 Implementation into ESP-r
Solving for C_o and n for Blower Door Inputs

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If the user inputs one of the standard leakage distributions, the simulator will set the building's fabric leakage coefficient (C_o) and the exponent (n) of the flow-versus-pressure equation according to the procedure described in Section 3.0 of Bradley (1993). The n coefficient is given in Table 3 on page 11 of Bradley (1993). The fabric leakage coefficient (C_o) is calculated by multiplying the house volume by the *normalized* leakage coefficient, which is also extracted from Table 3. The building's fabric leakage coefficient is the sum of the floor, ceiling, and wall leakage coefficients, and equals the building's total leakage coefficient minus the flue leakage.

When the user characterizes the leakage by a blower door test, however, a different procedure is required. In this case, the user gives three pieces of data to describe the leakage:

- ac/h_{50}, the air change rate (measured in house volumes per hour) at 50 Pa depressurization;
- ELA, the equivalent leakage area (cm^2) determined from the blower door test;
- $ELA_{\Delta P}$, the pressure difference at which ELA is specified (either 4 or 10 Pa).

C_o and n are determined by simultaneously solving two equations. The first defines the ELA. The form of the equation operated on here is based upon equation 30 from Bradley (1993, p10). However, the pressure difference is expressed here with $ELA_{\Delta P}$ rather than 10 Pa,

$$ELA = (12\,699.148) \cdot (C_o) \cdot (ELA_{\Delta P}^{n-0.5}) \tag{1}$$

The second equation is based on the general flow relation, $Q = C_o \cdot \Delta P^n$, evaluated at the 50 Pa depressurization and expressed in terms of ac/h (based on Bradley, 1993, equations 36 and 37),

$$\frac{ac/h_{50} \cdot VOL}{3600} = C_o \cdot 50^n \tag{2}$$

where VOL is the house volume (m^3).

By realizing that $ELA_{\Delta P}^{n-0.5} = \frac{ELA_{\Delta P}^n}{ELA_{\Delta P}^{1/2}}$, equation 1 can be expressed in terms of C_o by,

$$C_o = \frac{(ELA) \cdot (ELA_{\Delta P}^{1/2})}{(12\,699.148) \cdot (ELA_{\Delta P}^n)} \tag{3}$$

By taking the natural logarithm of both sides of the equation, equation 2 can be expressed by,

$$\ln\left[\frac{ac/h_{50} \cdot VOL}{C_o \cdot 3600}\right] = n \cdot \ln 50 \tag{4}$$

Substituting equation 3 into equation 4 and solving for n leads to,

$$\ln\left[\frac{(ac/h_{50}) \cdot (VOL) \cdot (12\ 699.148) \cdot (ELA^{n}_{\Delta P})}{(ELA) \cdot (ELA^{1/2}_{\Delta P}) \cdot (3600)}\right] = n \cdot \ln 50 \tag{5}$$

$$\ln\left[ELA^{n}_{\Delta P}\right] + \ln\left[\frac{(ac/h_{50}) \cdot (VOL) \cdot (12\ 699.148)}{(ELA) \cdot (ELA^{1/2}_{\Delta P}) \cdot (3600)}\right] = n \cdot \ln 50$$

$$n \cdot \ln\left[ELA_{\Delta P}\right] + \ln\left[\frac{(ac/h_{50}) \cdot (VOL) \cdot (12\ 699.148)}{(ELA) \cdot (ELA^{1/2}_{\Delta P}) \cdot (3600)}\right] = n \cdot \ln 50$$

$$n = \frac{\ln\left[\frac{(ac/h_{50}) \cdot (VOL) \cdot (12\ 699.148)}{(ELA) \cdot (ELA^{1/2}_{\Delta P}) \cdot (3600)}\right]}{\ln\left[\frac{50}{ELA_{\Delta P}}\right]}$$

The solution of equation 5 is then substituted into a rearranged equation 1 to yield,

$$C_o = \frac{ELA}{(12\ 699.148) \cdot (ELA^{n-0.5}_{\Delta P})} \tag{6}$$

Therefore, equations 5 and 6 have been incorporated into **SUBROUTINE AIM2_CandN** to solve for C_o and n when the user characterizes the house leakage with a blower door.

References

Bradley B. (1993), Implementation of the AIM-2 Infiltration Model in HOT2000, Unies Contract Report to NRCan.

AIM-2 Implementation into ESP-r
Solving for C_o and n for Blower Door Inputs When User Does Not Input ELA
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The HOT2000 version 8 interface allows the user to characterize the house's leakage with a blower door test result. Normally the user would supply the air change rate (measured in house volumes per hour) at 50 Pa depressurization (ac/h_{50}); the equivalent leakage area (ELA); and $ELA_{\Delta P}$, the pressure difference at which ELA is specified (either 4 or 10 Pa). However, by design the interface allows the user to neglect the ELA input. This document describes the procedure that is used in **SUBROUTINE AIM2_CandN** to calculate the building's fabric leakage coefficient (C_o) and the exponent (n) of the flow-versus-pressure equation in this case.

The following equation relates the ELA to the leakage coefficient (a modified form of equation 32 from Bradley, 1993, p9),

$$ELA = 11\,570 \cdot (1.205)^{1/2} \cdot C_o \cdot ELA_{\Delta P}^{n-0.5} \tag{1}$$

The following equation relates the air leakage measured in the blower door test to the leakage coefficient (equation 2 from Beausoleil-Morrison, 2000),

$$\frac{ac/h_{50} \cdot VOL}{3\,600} = C_o \cdot 50^n \tag{2}$$

where VOL is the house volume (m^3).

Solving equation 2 for C_o and substituting this into equation 1 gives a relation between the ELA and the two data input by the user,

$$ELA = \frac{11\,570 \cdot (1.205)^{1/2} \cdot ac/h_{50} \cdot VOL \cdot ELA_{\Delta P}^{n-0.5}}{3\,600 \cdot 50^n} \tag{3}$$

As described in the HOT2000 version 8 on-line help, the flow exponent (n) is fixed to 0.68 when an ELA is not input. Applying this assumption, equation 3 is solved to yield ELA. ELA and n are then used to solve for C_o using equation 6 from Beausoleil-Morrison (2000). Note that equation 5 from Beausoleil-Morrison (2000) is not applied in this case, since n is fixed to 0.68.

Note that this procedure differs somewhat from that applied in HOT2000 version 8. It applies equation 3 to calculate ELA, then uses this result to estimate n using equation 5 from Beausoleil-Morrison (2000). The calculated n is then used to determine C_o using equation 6 from Beausoleil-Morrison (2000). This approach was devised in the past in an effort to reduce the program's memory requirements: essentially it reduced by one the number of equations necessary to calculate the leakage coefficient. As a consequence, the flow exponent was not 0.68 is the infiltration calculations.

References

Bradley B. (1993), Implementation of the AIM-2 Infiltration Model in HOT2000, Unies Contract Report to NRCan.

Beausoleil-Morrison I. (2000), AIM-2 Implementation into ESP-r: Solving for C_o and n for Blower Door Inputs, NRCan Internal Report.

AIM-2 Implementation into ESP-r

Solving for R, X, and Y Leakage Distribution Parameters

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Subroutine AIM2_LEAKDIST determines the ceiling (α_1), floor (α_2), and wall (α_3) leakage fractions prior to commencing the time-step calculations. These express the fabric leakage in terms of fractions of the overall fabric leakage coefficient (C_o) and are defined by Bradley (1993, eq 9),

$$\alpha_1 = \frac{C_c}{C_o} \tag{1}$$

$$\alpha_2 = \frac{C_f}{C_o} \tag{2}$$

$$\alpha_3 = \frac{C_w}{C_o} \tag{3}$$

The fabric leakage distribution fractions are constrained to sum to unity,

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{4}$$

During the time-step calculations, subroutine AIM2_FLUELEAK is called to calculate the flue leakage coefficient (C_{flue}). This varies in time in response to the furnace's operation.

Subroutine AIM2_C_R_X_Y is called within the time-step loop immediately following the call to AIM2_FLUELEAK. The job of this subroutine is to calculate the *ceiling-floor sum*, *ceiling-floor difference*, and *flue fraction* leakage distribution parameters. These are defined by equations 3 to 5 in Walker and Wilson (1990). The derivation of these leakage distribution parameters from the leakage fractions is treated in this note.

Wilson and Walker (1990, eq 3) define the *ceiling-floor sum* parameter by,

$$R = \frac{C_c + C_f}{C} \tag{5}$$

where C_c is defined to be the leakage coefficient of the ceiling level leaks and C_f is the leakage coefficient for floor level leaks. C is the building's total leakage coefficient, defined to be the sum of the fabric leakage coefficient (C_o) and the flue leakage coefficient (C_{flue}),

$$C = C_o + C_{flue} \tag{6}$$

Similarly, the *ceiling-floor difference* parameter is defined by Wilson and Walker (1990, eq 4) as,

$$X = \frac{C_c - C_f}{C} \tag{7}$$

Finally, Walker and Wilson (1990, eq 5) define the *flue fraction* as,

$$Y = \frac{C_{flue}}{C} \tag{8}$$

The *ceiling-floor sum* parameter can be expressed in terms of the leakage distribution fractions. Firstly, equation 5 is multiplied by $\frac{C_o}{C_o}$,

$$R = \frac{C_c + C_f}{C} \cdot \frac{C_o}{C_o} \tag{9}$$

$$= \left(\frac{C_c}{C_o} + \frac{C_f}{C_o}\right) \cdot \left(\frac{C_o}{C}\right)$$

The term in the left parentheses of equation 9 is reduced by substituting in equations 1 and 2,

$$R = (\alpha_1 + \alpha_2) \cdot \left(\frac{C_o}{C}\right) \tag{10}$$

Rearranging equation 6 to solve for C_{flue} and substituting into equation 8 gives,

$$Y = \frac{C - C_o}{C} \tag{11}$$

$$= 1 - \frac{C_o}{C}$$

Rearranging equation 11 leads to an alternate form for the term in the right parenthesis in equation 10,

$$\frac{C_o}{C} = 1 - Y \tag{12}$$

Finally, substituting equation 12 into equation 10 leads to the equation implemented into subroutine AIM2_C_R_X_Y for calculating the *ceiling-floor sum* fraction,

$$R = (\alpha_1 + \alpha_2) \cdot (1 - Y) \tag{13}$$

The *ceiling-floor difference* parameter is similarly expressed by the following,

$$X = (\alpha_1 - \alpha_2) \cdot (1 - Y) \tag{14}$$

Equation 14 is implemented into subroutine AIM2_C_R_X_Y to calculate X while equation 8 is used to calculate Y.

References

Bradley B. (1993), Implementation of the AIM-2 Infiltration Model in HOT2000, Unies Contract Report to NRCan.

Walker I.S. and Wilson D.J. (1990), The Alberta Air Infiltration Model: AIM-2, University of Alberta Dept of Mech Eng, Report 71.