LoopDA: A NATURAL VENTILATION SYSTEM DESIGN AND ANALYSIS TOOL

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ABSTRACT

The Loop Equation Design Method has been proposed for sizing ventilation airflow components of natural and hybrid ventilation systems. While the loop design method has been demonstrated on a limited basis, the method has been automated in order to better evaluate its reliability under a more controlled, i.e., less error-prone, environment. This paper describes a computer program that implements the Loop Equation Design Method of sizing the openings of naturally ventilated buildings. The tool, referred to as LoopDA for Loop Design and Analysis, is integrated with the existing multi-zone IAQ model CONTAMW. LoopDA provides the designer of natural ventilation systems with an environment in which to perform and document the process of designing the opening sizes of natural ventilation systems and analyzing the system behavior under a variety of operating conditions. This paper describes the first version of the LoopDA program, provides an example of its application to the design of a naturally ventilated building and describes needs for future enhancements to the tool to increase its usefulness within the design community.

INTRODUCTION

The National Institute of Standards and Technology (NIST) is investigating the application of state-of-the-art natural ventilation concepts in commercial buildings and developing design methods for natural ventilation in new and retrofit applications. Earlier reports (Axley 2001a and Emmerich et al. 2001) reviewed the application of natural ventilation in commercial buildings including the associated technology, potential advantages of natural ventilation and issues that need to be addressed. The earlier reports also addressed opportunities and issues specific to the application of natural ventilation to commercial buildings in the U.S. including analysis of climate suitability via a new ventilative cooling metric, consideration of ambient air quality, and discussion of relevant codes and standards. They also reviewed current design and analysis processes and tools and described a plan for the development of new design and analysis guidance and tools.

A key recommendation of the earlier reports was to develop a software tool to implement the *Loop Equation D1esign Method* within the existing multi-zone modeling environment of CONTAM (Dols and Walton 2002) to gain the advantages of the existing user interface, airflow element base, and capability to perform detailed analysis after completing the natural ventilation system design. The *Loop Equation Design Method* (presented in detail by Axley 2001a) is a method for sizing of natural ventilation components that is general and practical and allows direct consideration of stack and wind-driven airflow that is critical in addressing natural ventilation airflow. Such a tool would assist the designer in performing the needed steps of developing the natural ventilation system design including: establishing the global geometry and topology of zones and interconnecting flow paths, establishing design conditions, setting up and solving the representative loop equations based on the "design" form of the airflow components, and analyzing operation under a variety of conditions.

This paper describes the first version of the LoopDA program (for Loop Design and Analysis tool) and an example application of LoopDA to the design of a natural ventilation system for a small commercial building. The LoopDA program is described in more detail in a separate report (Dols and Emmerich 2003) and is available at the NIST IAQ analysis website http://www.bfrl.nist.gov/IAQanalysis/default.htm.

LOOP EQUATION DESIGN METHOD

Axley (2001a) describes the Loop Equation Design Method that is proposed for the Design Development stage of the overall design process of a natural ventilation system in detail. (Note: The other design stages – Conceptual Design and Design Performance Evaluation – both precede and follow the Design Development Stage and are also described by Axley. Detailed theory of the method is presented in Axley 2001a and Axley 2001b.). The *Loop Equation Design Method* consists of the following eight steps:

1. Lay out the geometry and multi-zone topology of the natural ventilation flow loops for each zone of the building.

2. Identify an ambient pressure node and additional pressure nodes at entries and exits of each flow component along the loops.

3. Establish design conditions: wind pressure coefficients for envelope flow components, ambient temperature, wind speed and direction, and interior temperatures; evaluate ambient and interior air densities.

4. Establish first-order design criteria (i.e., a ventilation rate objective) and apply continuity to determine the objective design airflow rates required for each natural ventilation flow component.

5. Form the forward loop equations for each loop established in step 1 above by systematically accounting for all pressure changes while traversing the loop.

6. Determine the minimum feasible sizes for each of the flow components by evaluating asymptotic limits of the loop equation for the design conditions.

7. Develop and apply a sufficient number of technical or non-technical design rules or constraints to transform the under-determined design problem defined by each loop equation into a determined problem.

8. Develop an appropriate operational strategy to accommodate the regulation of the natural ventilation system for variations in design conditions.

As detailed in the following section, the user will perform some of these steps explicitly (e.g., Step1). Other steps are performed implicitly by LoopDA without user interaction (e.g., Step 5). Still others are accomplished by a combination of explicit and implicit actions (e.g., Step 3).

THE LOOPDA SOFTWARE TOOL

LoopDA was developed as a means to perform the eight steps of the *Loop Equation Design Method* presented in the previous section. While it does not fully automate all eight steps, it greatly simplifies and provides a means to manage the entire process. Specifically, the software accommodates each of the steps as follows:

1. LoopDA provides a SketchPad interface that enables the user to draw a schematic representation of the global geometry and multizone topology of the building and to draw the natural ventilation flow loops through the relevant airflow paths of the building.

2. The SketchPad provides the ambient pressure node and keeps track of the pressure nodes associated with each of the airflow paths that you identify on the SkethPad. The direction in which the user draws the loops establishes the intended direction of natural ventilation airflow for the purposes of design.

3. LoopDA provides for the establishment of design conditions by allowing the user full control in setting ambient conditions of temperature, wind speed and direction. It also enables the user to set the design temperatures of all airflow paths and then automatically calculates the air densities of each. The program also provides a means to input the wind pressure coefficient of all exterior openings.

4. LoopDA provides a means to define the first-order design criteria for each airflow path to be sized, however, the user must select the design criteria and ensure that continuity is not violated in the event that an opening serves multiple flow loops.

5. Once the user has established the geometry, design conditions and criteria and drawn the flow/pressure loops, LoopDA will form the forward loop equations for each loop by traversing the loop in the established direction and accounting for pressure changes due to the pressure/flow relationships of the various flow components, wind and stack effects.

6. LoopDA calculates the minimum feasible sizes of each unsized flow component in a loop by evaluating asymptotic limits of the loop equation for the design conditions.

7. LoopDA provides the ability to export loop information to a spreadsheet template (provided with the program) that displays all the data associated with a given loop, generates asymptotic plots and thus provides a means to view relationships between the flow components of a loop. This aids the application of design constraints, selection of component sizes and documentation of the steps in designing the natural ventilation airflow paths.

8. Having sized the natural ventilation airflow, the user can then utilize LoopDA to analyze the building performance under varying conditions. LoopDA implements the established multizone building simulation capabilities of CONTAMW 2.0 (Dols and Walton 2002). The user may perform an analysis to investigate the effects of unintentional air infiltration, non-design weather conditions, and forced-flow elements to simulate hybrid ventilation systems.

Design Approach Using LoopDA

This section present a brief over of the basic steps to take to implement the Loop Equation Design Method using LoopDA to size the airflow components of a natural ventilation system. Ideally one would perform the first four steps once for a given model of a building and iterate through the last two. These steps are not to be confused with the 8-step method presented previously.

- Define ambient design conditions
    Set temperature, wind speed and wind direction
- Draw the elevation view of the building
    Draw the walls
    Define the zones
- Draw ventilation airflow and duct flow paths to be sized
- Define airflow and duct flow elements
    Select inverse element type
    Set design airflow rate Q_{des}
    Set design temperature T_{des}
    Wind pressure coefficient $C_p(\theta)$
- Draw loops
    View loop data
    Export loop data
- Import into spreadsheet

DESIGN EXAMPLE USING LOOPDA

Sample Building

The use of LoopDA to design a natural ventilation system is demonstrated using an example from Axley (2001a). The sample building is based conceptually on the Inland Revenue Building in England (Irving and Uys 1997). It is worthwhile to note that, by using this sample building, the Conceptual Building phase mentioned above is already completed – allowing us to focus on the Design Development phase.

Figure 1 shows an elevation section view of this building model. As seen in the figure, the building is three stories tall with the 1st and 2nd floors being ventilated by air flowing in through inlet *orifices a* and *c* and out through a common exhaust stack represented by *zone s* and *opening h*. The 3rd floor is ventilated by air flowing in through two *self-regulating inlet vents e* and *f* (see Axley 2001a for a detailed description of these vents) and out through another exhaust stack represented by *opening g*. Each zone of the building has a volume of 800 m³.
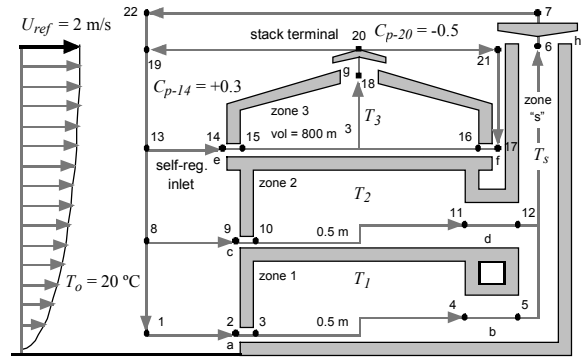

Figure 1 – Schematic and ventilation flow loops of a building model based on the Inland Revenue Building, England (Axley 2001a)

Design Conditions and Criteria

In addition to the global geometry presented in Figure 1, the designer must select indoor temperatures, outdoor temperature, wind speed, wind pressure coefficients, and ventilation flow rates to perform the design analysis. It is not obvious what values to select for many of these parameters. For example, it may not be sensible to select extremes (e.g., very low wind speed) for the design ambient conditions. Such extremes may rarely occur or may prove too severe a challenge for a pure natural ventilation system. For some climates, it may be necessary to either tolerate limited periods during which indoor environmental conditions will be outside design conditions considered typical for conventional, mechanically conditioned buildings or to provide some supplemental mechanical systems (i.e., a hybrid ventilation system) for such periods. That said, the procedure followed below provides a realistic example problem only and is not being proposed as formal guidance for determining design conditions for natural ventilation systems.

Emmerich et al. (2001) described a simple method to evaluate the suitability of a given climate to cool a commercial building with natural ventilation and went on to apply that method to ten California locations. That analysis indicated that the coastal climates of California are well suited to natural ventilation with respect to climatic considerations. Therefore, the building described above will be situated in San Francisco for the purposes of this sample application of LoopDA. Per the earlier climate suitability analysis, a natural ventilation system could potentially cool a commercial building with combined solar and internal heat gains of 10 W/m² to 80 W/m² greater than 90 % of the hours of the year with a supplemental night cooling system expected to be effective for any days that would be overheated based on direct ventilative cooling alone. Assuming a heat gain rate of 20 W/m² (a low but

achievable design target), the required average ventilation rate is 2.2 h^{-1} with a standard deviation of 2.6 h^{-1}. Therefore, a design ventilation rate of 5 h^{-1} (or about one standard deviation above the average) is a reasonable design objective for summer cooling. The coincident design indoor temperature for this summer condition may be selected as 26 ºC (based on the high end of ASHRAE's summer thermal comfort zone (ASHRAE 2001).

Figure 2 shows the hourly outdoor temperatures and coincident wind speeds for the San Francisco TMY2 weather file (Marion and Urban 1995). From Figure 2, it appears conservative to choose an outdoor temperature of 20 ºC with a wind speed of 2 m/s for the design conditions as hours with both higher temperatures and lower wind speeds are rare as shown by the dashed box.

Although it is typical to use a wind pressure profile that is dependent on wind direction (and possibly relative location of an opening on a wall), a single design value will be chosen for this example assuming the building will be oriented to take advantage of prevailing wind direction. Per Figure 16.7 of the ASHRAE Handbook of Fundamentals (ASHRAE 2001), a surface average wind pressure coefficient of 0.3 will be selected for the ventilation openings in the walls. Per Figure 16.9 of the ASHRAE Handbook of Fundamentals (ASHRAE 2001), a single value of -0.5 will be used for the wind pressure coefficient on the exhaust stacks.
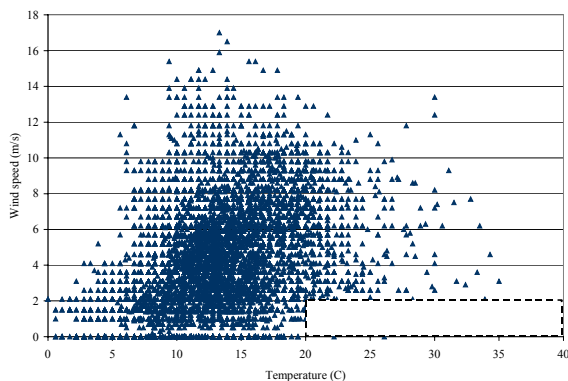

Figure 2 – Wind speeds vs. outdoor temperatures for San Francisco TMY2 weather file

Pressure Loops

With the building geometry and design conditions established, one may use LoopDA to form the loop equations and size the various natural ventilation system components. Figure 3 shows the LoopDA Sketchpad representation of the building elevation with the four pressure loops that must be analyzed. Loops 1 and 4 are equivalent loops following nodes 13-14-15-18-20-19-13 and nodes 21-17-16-18-20-21 serving *zone 3* (per Figure 1). Loop 2 follows nodes

8-9-10-11-12-6-7-22-8 serving *zone 2* and Loop 3 follows nodes 1-2-3-4-5-6-7-22-1 serving *zone 1*.
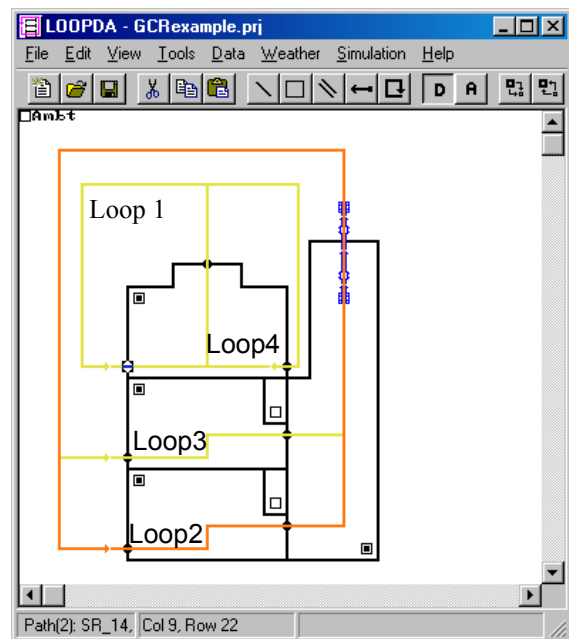

Figure 3 – LoopDA Sketchpad representation of natural ventilation design sample problem

Loops 1 & 4

Loops 1 and 4 are equivalent loops each providing 0.55 m^3/s (half of the design 5 h^{-1}) to *zone 3* via self-regulating inlet vents. Both loops exhaust through the *stack terminal g* on Figure 1 for a total design flow of 1.1 m^3/s through the stack terminal. The self-regulating inlet vents are modeled in LoopDA as power law flow elements with an exponent of 0.1 (see Axley 2001a for more information) and an undetermined characteristic design parameter (CDP) C_e (see Figure 4). The stack terminal is modeled as an orifice with the area $A_{orfc,g}$ (refered to as *Aorfc1* by LoopDA) as the CDP. The complete pressure loop properties from LoopDA are shown in Figure 5.
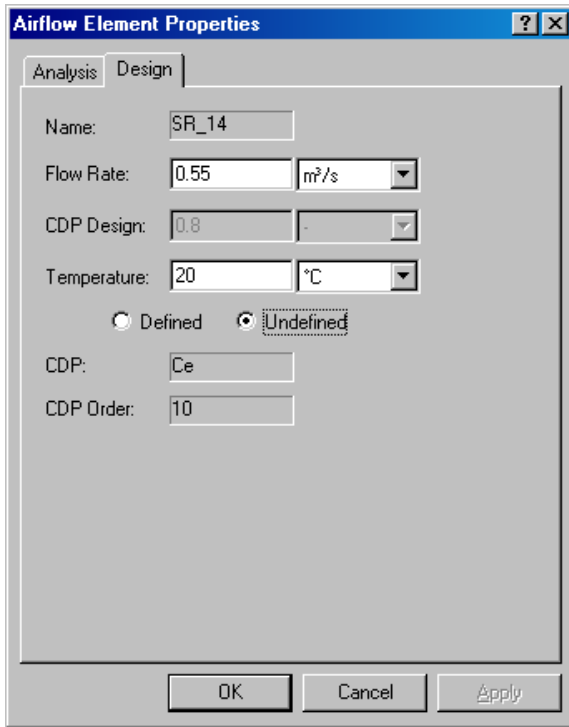
Figure 4 – Airflow element design window

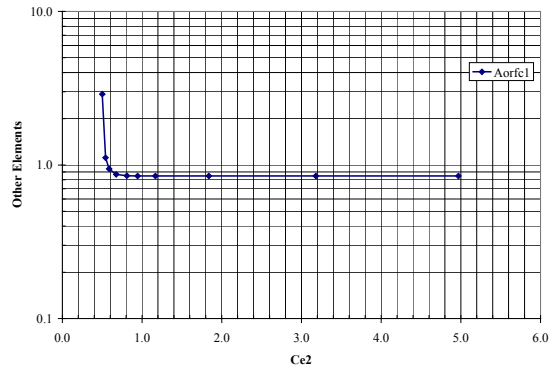Figure 5 – Pressure loop properties window for for the self-regulating inlet vent of Loop 1

After entering the information for Loop 1, the loop data are exported to a tab-delimited file that is pasted into the LoopDA spreadsheet template. Since Loop 1 has only two elements with undetermined CDPs, the LoopDA template plot is simple and shows the sizing relationship between C_e and $A_{orfc,g}$ (see Figure 6). From Figure 6, the CDP for either element may be chosen (based on other considerations such as available component sizes from catalog data) and the minimum required size for the other CDP is fixed. For this example, selecting a value of 0.8 for C_e dictates a minimum orifice area of 0.85 m², which might be rounded up to 1.0 m² based on availability.

Figure 6 – Asymptotic relationship between CDP of self-regulating inlet vent Ce (Ce2) and CDP of stack terminal $A_{orfc,g}$ (Aorfc1) for Loop 1

Loop 2

Loop 2 supplies 1.1 m³/s (i.e., 5 h⁻¹) to *zone 2* via *inlet c* on Figure 1. The flow exhausts through *outlet d* into the stack zone s and out the *stack terminal h* on Figure 1. Note that the stack must also exhaust the ventilation flow from *zone 1* for a total design flow of 2.2 m³/s through the stack. The inlet and outlet vents are modeled in LoopDA as orifice flow elements with $A_{orfc,c}$ (*Aorfc5*) and $A_{orfc,d}$ (*Aorfc4*) as the undetermined CDPs. The stack is modeled using a Darcy-Colebrook duct model with an orifice as the inlet (the CDP is the area *A3*), an orifice as the outlet (the CDP is *A1*), and a 1 m long round duct segment (the CDP is the duct diameter *D3*). The complete pressure loop properties from LoopDA are shown in Figure 7. Note that, if desired, the user must impose the condition that the stack orifice areas be based on the duct diameter during the sizing process as LoopDA treats them as independent CDPs.
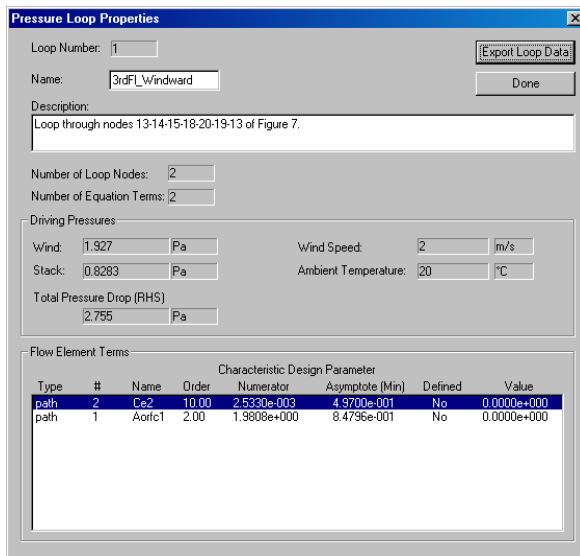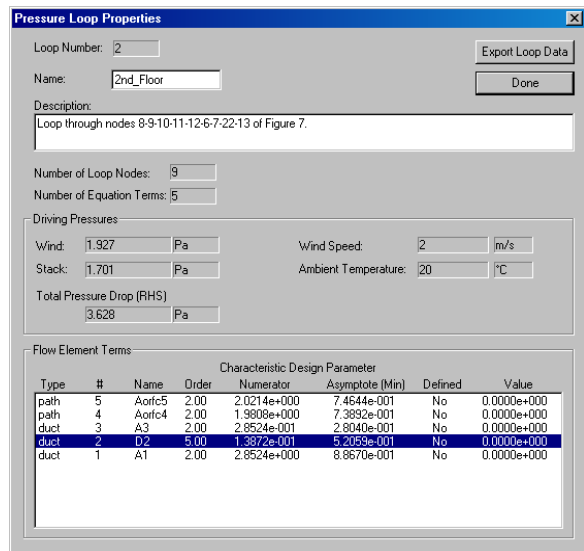

Figure 7 – Pressure loop properties window for Loop_2

After entering the information for Loop 2, the loop data are exported to a tab-delimitted file which is pasted into the LoopDA spreadsheet template. Loop 2 has only five elements with undetermined CDPs (although $D2$, $A1$, and $A3$ are related). Figure 8 from the LoopDA template plot shows the sizing relationship between $D2$ and all other CDPs. From Figure 8, $D2$ will be set at 1.2 m. Basing the stack inlet and outlet areas ($A1$ and $A3$) on this diameter sets these areas at 1.1 m^2 (which is larger than the minimum requirements for these areas per Figure 8).
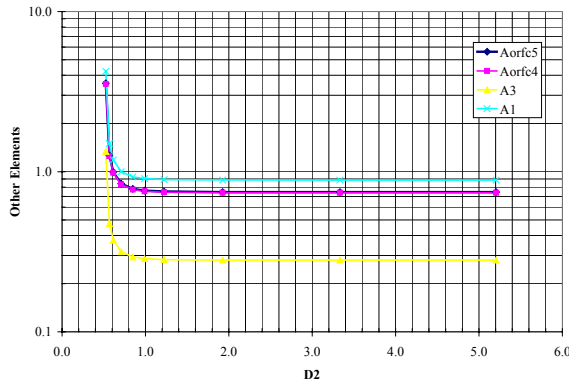

Figure 8 – Asymptotic relationships for Loop 2

Unlike Loop 1, Loop 2 still has undetermined CDPs. Returning to the LoopDA sketchpad, entering the parameters established for the stack duct and terminals ($D2$, $A1$ and $A3$), and exporting Loop 2 (see Figure 9 for the pressure loop properties) for a second time yields a second worksheet for this loop.
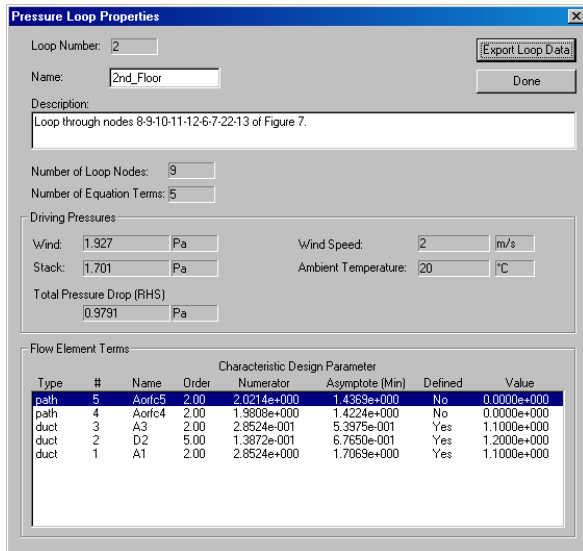

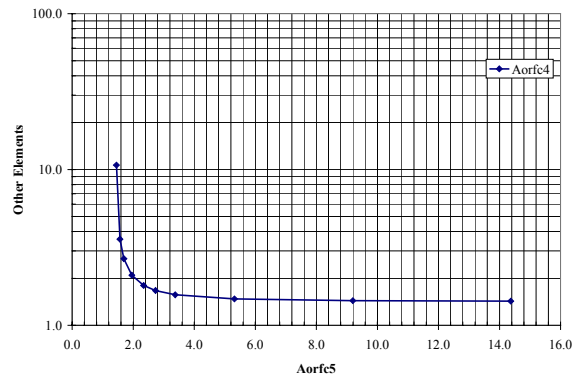*Figure 9 – Loop 2 pressure loop properties after setting the sizes of D2, A1 and A3*

Figure 10 – Asymptotic relationship of remaining undetermined CDPs for Loop 2

As seen in the worksheet and Figure 9, $A_{orfc,c}$ (*Aorfc5*) and $A_{orfc,d}$ (*Aorfc4*) remain to be selected. *Figure 10* shows the asymptotic relationship between these remaining undetermined CDPs. From *Figure 10*, the inlet *Aorfc5* will be selected as 2.0 m^2, which sets the minimum outlet *Aorfc4* also at approximately 2.0 m^2.

Loop 3

Loop 3 consists of the same type of elements as Loop 2 – *inlet orifice a* (*Aorfc7*), *outlet orifice b* (*Aorfc6*), and the shared *stack exhaust g*. As seen in Figure 11, the previously defined stack CDPs are retained leaving only the inlet and outlet of *zone 1* to be defined. The LoopDA spreadsheet is similar to the second Loop 2 worksheet. The asymptotic relationship between the undetermined CDPs *Aorfc6* and *Aorfc7* is shown in Figure 12. Selecting the outlet to be the same as for zone 2 at 2.0 m^2 sets the minimum size for the inlet Aorfc7 at approximately 1.3 m^2.
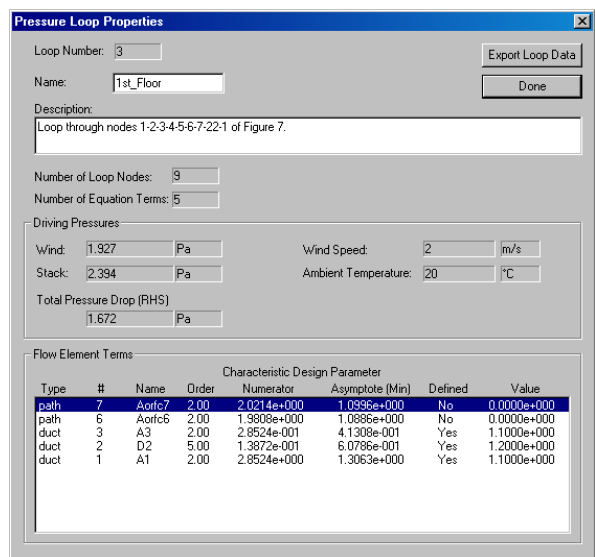

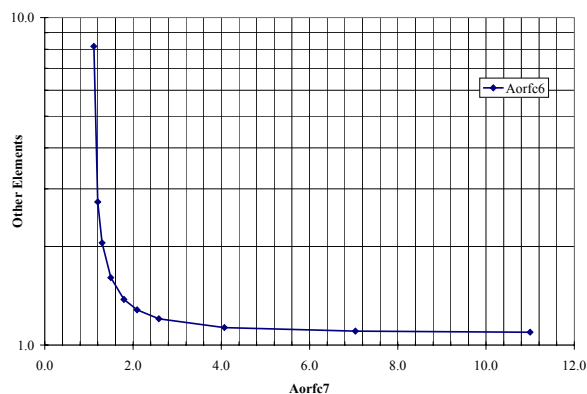*Figure 11 – Pressure loop properties window for Loop 3*

Figure 12 – Asymptotic relationships for Loop 3

Design Summary and Analysis

The completed design of the four ventilation loops is summarized below in Table 1.

Table 1

Design values of sized components

Loop	Element	CDP		Size
		Figure 1	LoopDA	
1	Self-reg. inlet vent	C_e	Ce2	0.80
1	Stack terminal	$A_{orfc,g}$	Aorfc1	1.00
2	Inlet	$A_{orfc,c}$	Aorfc5	2.00
2	Outlet	$A_{orfc,d}$	Aorfc4	2.00
2	Stack inlet	$A_{stack\ in}$	A3	1.13
2	Stack diameter	$D_{stack\ duct}$	D2	1.20
2	Stack outlet	$A_{stack\ term}$	A1	1.13
3	Inlet	$A_{orfc,a}$	Aorfc7	1.30
3	Outlet	$A_{orfc,b}$	Aorfc6	2.00
3	Stack inlet	$A_{stack\ in}$	A3	1.13
3	Stack diameter	$D_{stack\ duct}$	D2	1.20
3	Stack outlet	$A_{stack\ term}$	A1	1.13
4	Self-reg. inlet vent	C_e	Ce3	0.80
4	Stack terminal	$A_{orfc,g}$	Aorfc1	1.00

LoopDA may now be used to analyze the completed design by performing simulations ranging from steady state under non-design conditions to a seasonal or annual analysis using TMY2 or other weather data for the location. One condition that could be analyzed is the potential for excess outdoor airflow under a winter condition. Referring back to Figure 2, an outdoor temperature of 5 ºC and a wind speed of 8 m/s will be used. Also, the wall opening wind pressure coefficients will be increased to 0.6 to increase the impact of wind for this case. The indoor temperature is set to 20 ºC for this case.
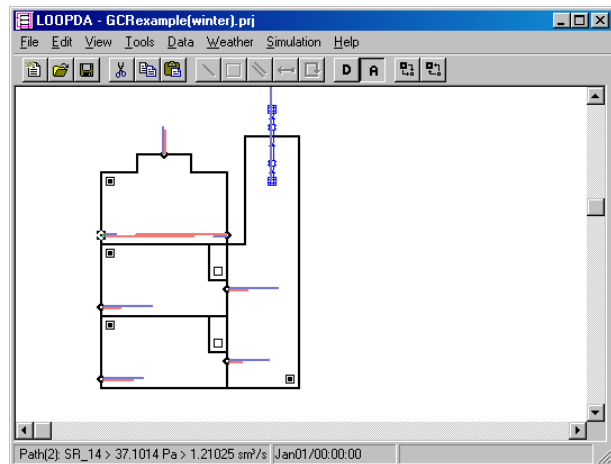

Figure 13 – Simulation results for winter condition analysis. Blue lines indicate direction and relative magnitude of airflow (note: status bar indicates a flow of 1.21 sm³/s for the self-regulating inlet vent)

The results of the design analysis of a winter condition are shown in Figure 13. This analysis shows the risk of greatly over ventilating the space if no provision is made for altering the ventilation openings under a winter operating condition as the flow into zones 1 and 2 increases to 3 to 4 times the design flow. The self-regulating inlets perform better but the outdoor airflow still doubles from the design case. For a real building, the designer would likely specify a desired minimum winter ventilation flow and then use LoopDA in design mode to determine desired vent opening sizes in a winter mode. An operational strategy could then be established whereby, for example, half of the openings are used during winter operation.

CONCLUSION

LoopDA was developed to demonstrate the implementation of the *Loop Equation Design Method* within an existing multi-zone modeling environment. It provides designers with a framework for implementing the design method in order to become familiar with the method, to explore the practicality of using this method within the overall natural ventilation system design process, and to provide feedback to the developers as to the potential for this tool for use in the design and analysis of natural ventilation systems.

Since this is a new program, many potential enhancements exist and some have already been identified including: the implementation of a more diverse set of inverse flow component types, more robust user interface features and consideration for the design of mechanical components of hybrid ventilation systems. In general, inverse airflow

elements are relatively easy to add to the existing environment. However, depending on the element type, the inverse solution to sizing some elements could prove to be more difficult than others, e.g., a polynomial fan curve. The user interface could be improved by eliminating the need for the external spreadsheet; providing automated population of analysis components based on design component sizes; verifying continuity of flow through components serving multiple loops; generation of reports summarizing design conditions and system design, enabling the application of a more diverse set of design constraints, e.g., requiring duct inlet, outlet and segments of the same size or providing a direct means to consider infiltration.

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