APPLICATION OF A NATURAL VENTILATION SYSTEM DESIGN TOOL TO A SCHOOL BUILDING

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ABSTRACT

A software tool (LoopDA) to aid in the design of natural ventilation systems has recently been updated. This update implements a general method for sizing of natural ventilation system components, which allows direct consideration of stack and wind-driven airflow. The tool assists the designer in performing the following steps in developing the natural ventilation system design: 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 updated tool and provides an example of its application to the design of a naturally ventilated school building.

INTRODUCTION

In earlier work [Dols and Emmerich 2003, Emmerich and Dols 2003], the National Institute of Standards and Technology (NIST) developed a software tool to implement the Loop Equation Design Method [Emmerich et al. 2001]. That method enables the sizing of natural ventilation components in a general and practical manner, and allows direct consideration of stack and wind-driven airflows that are critical in natural ventilation. The tool assists the designer in performing the steps in designing natural ventilation systems 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.

Version 1.0 of the LoopDA program (for Loop Design and Analysis tool), was developed as a version of CONTAM. LoopDA 1.0 has been upgraded to version 3.0 to correspond to the latest version of CONTAM 3.0 [Walton and Dols 2005]. Further, LoopDA 3.0 has been modified to streamline the process of implementing the Loop Equation Design method mainly by eliminating the need for a third party spreadsheet during the design process. It also incorporates a simple thermal design calculation to assist in estimating design temperatures and natural ventilation airflow rates, adds self-regulating vents as an airflow component option (Axley 2001a), and calculates fractional bias as a measure of the adequacy of simulated airflow results relative to design requirements. This paper provides an overview of the steps involved in implementing the Loop Equation Design within LoopDA 3.0, reviews the input requirements, and presents a brief design example of how to utilize the tool.

SIMULATION METHOD AND IMPLEMENTATION

Loop Equation Design Method

The Loop Equation Design Method, which is intended for use during the Design Development stage of the overall design process of a natural ventilation system, is described in detail in Emmerich, et al. [2001]. (Note: The other design stages, Conceptual Design and Design Performance Evaluation, precede and follow the Design Development Stage respectively and are described in this same reference.) 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 global 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; calculate indoor and outdoor air densities.

4. Establish first-order design criteria (i.e., a ventilation requirement) 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., Step 1). 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).

Using the LoopDA 3.0 GUI to Implement the Loop Equation Design Method

The following steps are followed to utilize LoopDA 3.0 to implement the Loop Equation Design Method. Note that these steps do not align perfectly with those presented in the Loop Equation Design Method section, but they do address all of the steps needed to implement the method.

1. Define project default Design Data via the Calculations menu. These include the outdoor temperature, wind speed and atmospheric pressure for the current design condition being analysed.

2. Use the Box and Line drawing tools provided in the toolbar to draw the outlines of the zones. This drawing will form an elevation view of a section of the building through which natural ventilation is to be provided.

3. Place zone icons and define the zone properties. Set the minimum required ventilation rates (e.g., based on ASHRAE Standard 62.1) and the thermal characteristics of the zone (e.g., internal loads) in order to establish the ventilative cooling airflow rate required to maintain the zone at a design temperature for the design conditions.

4. Place airflow path icons on the walls that connect the zones. You can also use the duct drawing tool to draw ducts. It is best to draw all the sections of

a duct before defining them. A typical duct will have three sections: inlet fitting, segment, and outlet fitting, with each section separated by a junction icon.

5. Define each of the undefined flow paths and duct segments by setting the properties as desired via the associated dialog boxes that will be displayed. You will be prompted to select the type of airflow or duct flow element that is being used to represent the relationship between airflow and pressure drop through the flow path, e.g., powerlaw, orifice or self-regulating vent, or the duct, e.g., segment or terminal/fitting. These are mathematical models that relate the airflow to the pressure difference across the path. These are akin to the airflow elements in CONTAM, but LoopDA provides both forward and inverse forms of each model. The inverse forms of the equations are used when forming the pressure loop equations during the sizing phase of the design procedure, while the forward forms are used when performing a simulation to verify the design.

6. Use the Loop (Arrow) drawing tool to draw intended airflow patterns (pressure loops) through the flow paths and ducts. Begin drawing outside of the building and draw in the direction that you want air to flow through the airflow paths. Drawing will stop when you have exited the building via a flow path or duct. Note that the arrows you draw represent the pressure conservation concept of the Loop Equation Design Method.

7. Define design conditions for the case you are working on via the Design Data dialog box available under the Calculations menu:

   a. outdoor temperature and wind speed

   b. zone cooling and heating set point temperatures: Tcsp and Thsp

8. Access the Simple Thermal Design dialog box via the Calculations menu to:

   a. review required airflow rates for each zone

   b. set airflow rates for each loop based on required airflow rates

   c. perform the Simple Thermal Design calculation to balance airflows and determine temperatures for each zone, airflow path and duct

The Simple Thermal Design calculation is a simplified cooling load calculation that includes convective heat gain/loss via airflow into/out of the zone, conductive heat loss through the exterior envelope based on an overall heat transfer coefficient and the sum of heat sources (internal, solar, etc.). However, it does not

account for differences in solar incidence on various building surfaces, fenestration effects, transient conduction, and other heat transfer mechanisms.

9. Double click each loop arrow icon to reveal the Pressure Loop Properties dialog and review the asymptotic relationships between the components to be sized. This analysis utilizes the *inverse* form of the airflow elements to present the feasible design curves. Set each component to be sized in turn until they have all been defined.

10. Steps 1 - 9 essentially form the design portion of the process for a given set of design conditions (e.g., outdoor temperature and wind speed). Once the design portion of the process has been completed for a given set of design conditions, use the Run Simulation command under the Calculation menu to perform an analysis calculation. This will calculate the airflow rates for the combination of sizes you selected.

11. After the simulation has been successfully run, the SketchPad switches to the results display mode. In this mode, scaled lines will be displayed to provide relative airflow rates and pressure difference across each airflow path and duct terminal icon, and the status bar/tool tip will provide numerical results. Airflow results will be provided in both mass flow and volume flow units along with the fractional bias (FB) between the mass flow as calculated by the simulation (Q_{sim}) and that determined via the Simple Thermal Design calculation (Q_{calc}).

Fractional bias provides a normalized range of values between ± 2.0 and is very similar to percent difference for values between ± 25 %. Values of FB between ± 1.636 indicate that averages are within one order of magnitude of each other, and values between ± 1.960 are within two orders of magnitude of each other.

12. Steps 7 through 11 are repeated for each set of design conditions thus establishing the range of sizes required to meet the various conditions that are expected to be encountered for the building. To perform these steps for another set of conditions, you should save the project under a new name, then Unsize All Elements via the Calculations menu, and repeat steps 7 through 11.

DESIGN EXAMPLE

The following example provides a brief tutorial on how to utilize LoopDA to size the natural ventilation openings for a single zone case. Figure 1 provides a schematic diagram of a cross section of the room, which is based on a case provided by [Daly 2003].

Run LoopDA and edit the Design Data as follows:

- Outdoor Temperature = 23.3 °C (74 °F)
- Wind Speed = 1.56 m/s (3.5 mph)
- Indoor Design Temperature = 28.9 °C (84 °F)
- Room dimensions: 12.19 m x 7.32 m x 3.96 m (L x W x H_{avg}) (40 ft x 24 ft x 13 ft)

Draw the SketchPad diagram as shown in Figure 2. Begin by drawing the zone outline, then place the zone icon and each of the path icons. Define the zone and path icons as provided in the dialog box figures that follow. Figure 3 provides the zone data for this design case where the input in the white boxes is entered by the user (including the zone dimensions, minimum ventilation requirements, thermal design parameters, and set points) while the values in the shaded boxes are calculated by the program.
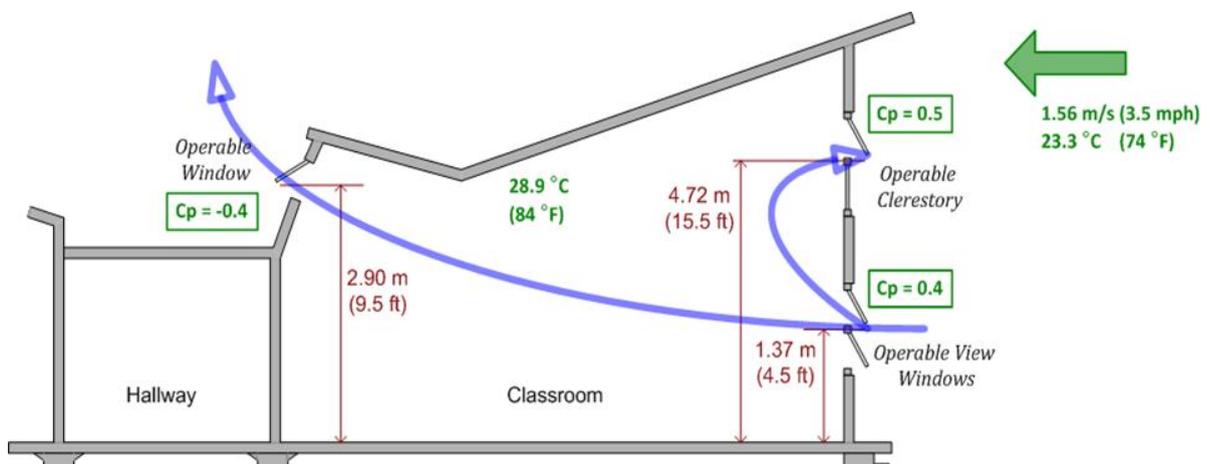

Figure 1 - Conceptualization of Classroom Natural Ventilation Design

The next step is to define the path properties for the numbered icons as shown in Table 1.

Table 1 - Path properties

Number	Type	Name	Elevation m (ft)	Cp
1	Orifice	Clerestory	4.72 (15.5)	0.5
2	Orifice	UpperWindow	2.90 (9.5)	-0.4
3	Orifice	InletWindow	1.37 (4.5)	0.4
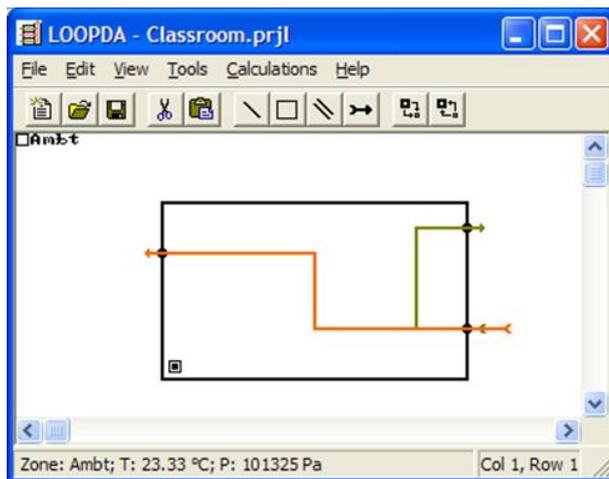
Figure 2 - SketchPad showing zone, paths and loops

Open the Simple Thermal Design dialog box via the Calculations menu. Set the airflow rates for the two loops to overcome the heat sources within the zone (cooling load). The value of Q_{cool} should be 1888 L/s (4000 cfm) for both loops as they each serve the same zone. Because both loops enter through the same flow path, you need to apportion some of the flow to each loop. Set the design flow of each loop to 944 L/s (2000 cfm) and click the Perform Simple Thermal Design Calculation button. The results for both loops appear as shown in Figure 4. Note that the loop components are provided from top to bottom in the order in which the air flows through them: 1888 L/s (4000 cfm) into path 3 (InletWindow) and 961.7 L/s (2038 cfm) out of both paths 1 and 2. Note that in order for a mass balance to be maintained, a greater volume of 28.9 °C (84 °F) air must flow out due to the lower density of the exiting air.

After the simple thermal design has been performed, the airflow rates and temperatures for each of the airflow paths (and zone) will be set. When you open each of the corresponding dialog boxes, this will be evident by the Qcalc and Tcalc values presented therein. It is now time to set the sizes of each airflow component.

Starting by double clicking Loop 2 (through paths 3 and 1) to reveal the Pressure Loop Properties dialog box shown in Figure 5.

Additionally, you can click the "Show Graphs" button to reveal the size relationship graph between the two openings (Aorfc2 vs. Aorfc3) as shown in Figure 6.
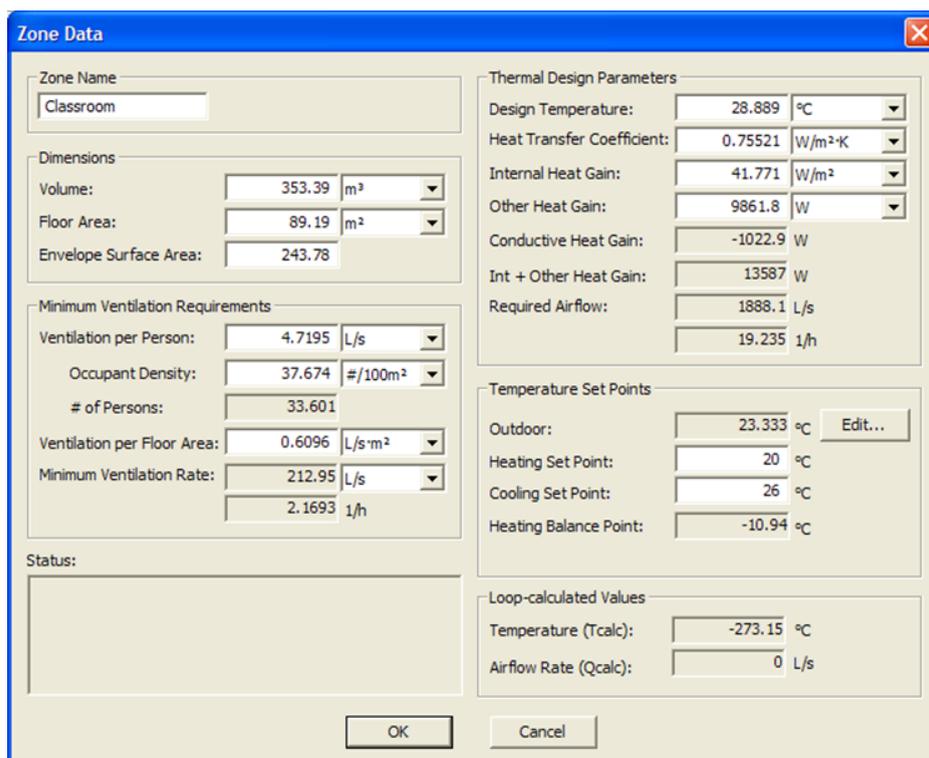

Figure 3 - Zone properties

This graph indicates the minimum size limits that are approached asymptotically as either flow element (opening) is allowed to be unlimited in size in which case the minimum size would be necessary in order to limit the flow for the given design conditions. These minimum limits are provided in the Pressure Loop Properties dialog. The solid line on the graph indicates the relationship when both stack and wind are driving the natural ventilation flows, and the dashed line provides the stack-only relationship. One can see that the stack-only relationship requires larger openings in order to meet the flow requirements.

The dialog box indicates the minimum value for Aorfc3 is approximately 2 m^2 (21.5 ft^2) for the Stack & Wind condition and 4.2 m^2 (45.2 ft^2) for the Stack Only condition. The chart reveals that a value of 10 m^2 (107.6 ft^2) should provide little resistance to airflow for either case.

Close the chart and loop dialog box and edit path number 3 by double clicking on it. Set the Orifice Area to 10 m^2, set it as Sized and click the OK button. Open the Loop 2 properties again and note that the minimum size for Aorfc2 (path 2) is given as 1.023 m^2. Set the orifice area of the UpperWindow (path 2) to 1.023 m^2 (11.01 ft^2) and set its Sized property. Repeat this process to set the orifice area of Clerestory (path 1) to 1.71 m^2 (18.41 ft^2). Now that all of the openings have been sized, when you display the loop properties, the Total Pressure Drop (RHS) value for the case you are sizing (Wind & Stack) should be very close to zero.

You can now analyze this design by running the simulation via the `Calculations -> Run Simulation` menu command. This command will perform a steady state airflow calculation using the CONTAM simulation engine. The SketchPad will now be in the Results Display mode as indicated by the scaled lines (**red** = pressure difference and **green** = airflow rate) emanating from the flow paths. You can hide the pressure loops and highlight the path icons to view the simulation results and compare them with the design values as shown in Figure 7. Note the fractional bias (FB) provides a means to compare the simulation results to the design values. The results presented in Figure 7 show that the flow rate based on the analysis calculation matches the design requirement (the "Required Airflow" shown in the dialog box in Figure 3) very closely with a FB of 0.08 %. In this case an airflow rate of 1889.45 L/s offsets the thermal gains to maintain a zone temperature of 28.89 °C. This resultant temperature can be revealed via the SketchPad by clicking on the zone icon.

You could then repeat these steps to size the openings for the Stack Only case and other weather conditions. You should save this project file under a new name to work with the next set of condition. You can unsize all the elements via the `Calculations -> Unsize All Elements` command to begin the process.

DISCUSSION AND CONCLUSION

This paper has described LoopDA 3.0 - a new software tool that assists in the design of natural ventilation systems. The software's key technical innovation is the capability of solving the inverse form of the airflow-pressure equation to present the user with a graphical presentation of the range of potential solutions for the sizing of natural ventilation components (e.g., inlet vents, ducts, etc.). Other new technical features include a built-in simple thermal design calculation to determine required natural cooling airflow rates, addition of self-regulating vents as an airflow component option (Axley 2001a), and calculation of fractional bias as a measure of the adequacy of simulated airflow results relative to design requirements.

ACKNOWLEDGMENT

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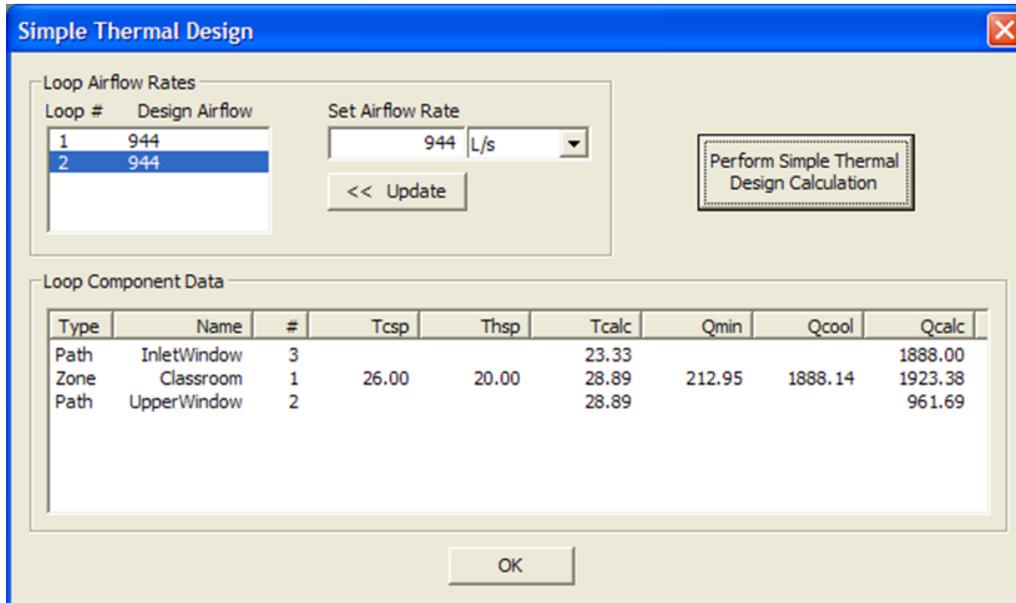
Figure 4 - Simple Thermal Design Dialog box showing the result of Loop 1 after calculation has been performed
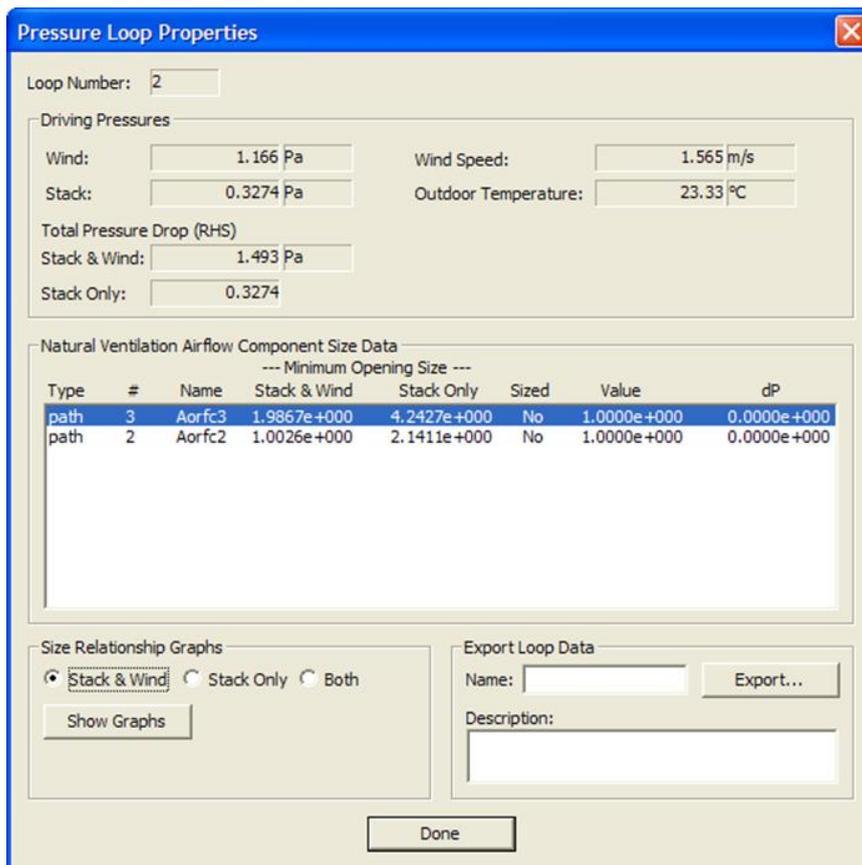

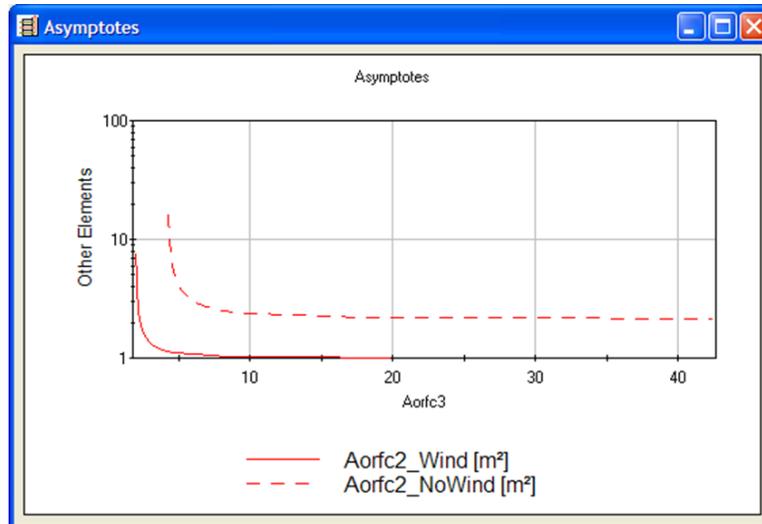*Figure 5 - Pressure Loop Properties dialog box*

Figure 6 - Plot showing relationship between sizes of two openings for both the Wind & Stack and Wind only design conditions
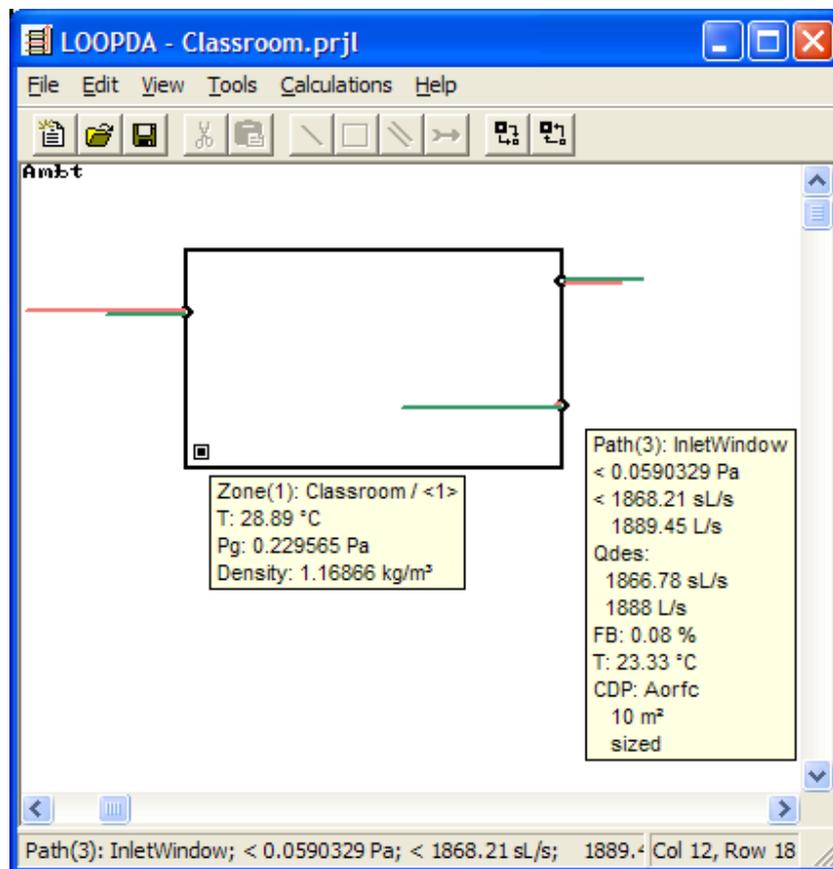

Figure 7 - SketchPad display of analysis calculation (ContamX simulation) results