DESIGN AND VERIFICATION OF A PARTIAL RECIRCULATION COOLING SCHEME FOR A TELECOMS SHELF

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ABSTRACT

Flow Network Models were used to design an innovative cooling system for a telecoms shelf which uses the partial recirculation of air to increase air velocities over the circuit cards. The paper is divided into two parts. The first part of the paper outlines the design of the recirculation cooling system, an outline of the design objectives, and a description of the Flow Network Model used. The second part of the paper outlines the measurements of the flow within the shelf. Flow measurements were performed with an Airflow Test Chamber (obstruction type flow meter) to measure bulk flow from which average slot velocities were calculated. These results are compared with the original Flow Network Model simulation results. Comparison of the measured and modeled data shows that there is a very close agreement in bulk flow prediction except for the recirculation bulk flow rate, and that difference was due to a much higher than anticipated density of power cables routed across the recirculation duct.

KEY WORDS: flow network modeling, flow measurement, system level design, recirculation, forced air cooling

NOMENCLATURE

P	Pressure
V	Velocity
n	Exponent (between 1 and 2)

INTRODUCTION

Telecoms systems must be designed to meet customer requirements such as those outlined in NEBS (“Network Equipment Building System”) [1]. These requirements provide the operating framework (ambient temperature, altitude above sea level) for the system level design of telecoms enclosures. Alcatel has recently released a high-speed core switch product (the 7670 50 Gig Enclosure) which meets NEBS requirements through the innovative use of a partial recirculation air cooling system. The recirculation of air within the enclosure enables higher air velocities over critical components than would otherwise be possible with a “straight through” cooling system.

The successful design of the recirculation system required an intensive modeling exercise at the initial stages of the project. The modeling cycles were performed using MacroFlow [2], which is a commercial Flow Network Modeling software package. The key objective of the modeling cycles was to establish the necessary mechanical design parameters (such as intake / exhaust baffle dimensions) required to provide the desired air velocities while avoiding an excessive air temperature rise within the enclosure. The modeling was performed in conjunction with the mechanical and industrial design teams to ensure that both airflow and manufacturability constraints were met in the final design.

A prototype enclosure was obtained in order to ensure that the system level design targets (bulk air flow and average air velocities) were achieved. Bulk airflow was measured using an Airflow Test Chamber, which is an obstruction type flow meter that measures airflow by measuring the pressure drop across a calibrated obstruction.

OVERVIEW OF FLOW NETWORK MODELING

Flow Network Modeling is used to calculate fluid flow rates in a system by modeling the system as a network of flow elements (fans, ducts, elbows, tees, etc). This technique is analogous to electrical circuit network modeling except that the calculated quantities are *fluid flow rates* and *pressures* as opposed to *current* and *voltage*s for electrical circuits.

A Flow Network Model is created by defining all elements and nodes in a system. Elements and nodes are of the following types:

(1) Sources elements, such as fans or pumps.
(2) Resistance elements, such as card cages, air filters, ducts or louvers.
(3) Nodes, such as plenums.

Flow Network Models may be solved by a variety of techniques, ranging from spreadsheet analysis to commercial codes. Common to all techniques is the requirement that mass and momentum conservation equations are satisfied for each element of the network.

The present work used a commercial code, MacroFlow, which is based on the SIMPLE algorithm of Patankar [3]. This algorithm hinges on iteratively calculating the nodal pressures and the flow rates through all elements. The flow rates through the elements are calculated based on the momentum equation using the existing *nodal* pressures (from the previous iteration). The nodal pressures are, in turn, calculated based on existing *element* flow rates (calculated in the previous iteration).

The key to creating a useful Flow Network Model is accurately defining the constituent models for each element (Table 1). Fan curves are typically obtained through direct measurement on an obstruction type flow meter (figure 1). Flow rate through the flow meter is measured indirectly by measuring the differential pressure across a calibrated nozzle. The pressure rise across the fan is measured using the static pressure tap (figure 1) which is located upstream of the fan. By varying the flow through the flow meter (by means of a blower and a 'blast gate') a series of pressure-flow rate data points may be obtained which are then used to define the fan curve.

The obstruction type flow meter may also be used to define the resistance characteristics of a resistance element. This is typically necessary if the resistance element represents a geometry that is not referenced in the open literature. Many resistance elements represent "standard" or "default" geometry (such as punched plates or ducts) which have known pressure – flow rate relations. These relations are typically built into commercial Flow Network Model software packages.

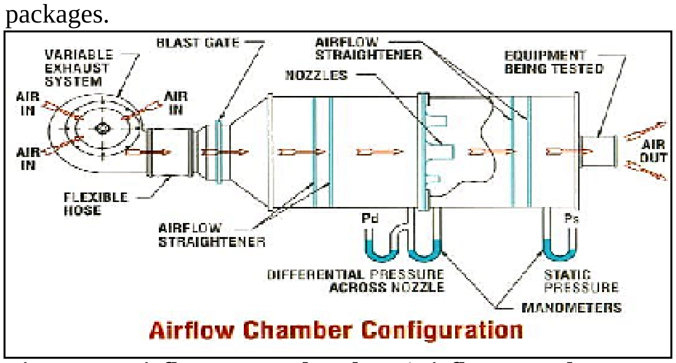

Figure 1. Airflow Test Chamber (Airflow Developments, Inc.)

Table 1: Flow Network Model Definitions

TYPE	FORM OF MODEL	SOURCE OF MODEL PARAMETERS
Air Mover (fan, blower)	Fan curve relating pressure and flow rate.	Obstruction type flow meter.
Resistance Element - Default	Often defined using a Loss Coefficient, k: $\Delta P = k\frac{1}{2}\rho V^{n}$	Open Literature, Example: Idelchik [4]
Resistance Element - Measured	Resistance curve relating pressure and flow rate.	Obstruction type flow meter.
Node	Conservation of Mass, Conservation of Momentum.	Physical Geometry

SYSTEM DESIGN OBJECTIVES

The initial stage of system level thermal design involves identifying the system design objectives. The goals of system level thermal design are:

1. Meet defined requirements for overall air temperature rise within the system.
2. Meet target air velocities over circuit cards.

For "Central Office" environments in North America these goals must be met within the context of NEBS (Bellcore Document GR-63-CORE) that outlines operating requirements for telecommunications equipment within North America.

Central Office Design Constraints

The system design constraints listed below are defined in NEBS (Bellcore GR-63-CORE) [1].

- Functionality is maintained for 96 hours at 50°C for a 96 hour period.
- Maximum operational altitude of 1800 meters.
- Room dust loading of 20 micrograms/m^3.
- Noise limit of 60 dBA (600 mm perimeter, 1500 mm height).

These design constraints provide the framework for the system level thermal design of any telecoms enclosure.

System Design Objectives – 7670 50 GigEnclosure

The system design objectives for the enclosure are listed below. The authors in conjunction with the Hardware Development team defined these requirements. At the time of the system level design, specific PCB level design parameters were not final. Maximum slot velocities with a limit on bulk temperature rise formed the basis of the design targets to mimimize the thermal risks at the PCB level.

1. Target System Power Budget : 4000 W.
2. Target Line Card Slot Air Velocity: 2.3 m/s.
3. Target I/O Card Slot Air Velocity: 2.5 m/s.
4. Allowable Air Temperature Rise: 20°C.

DESCRIPTION OF RECIRCULATION DESIGN

The initial stage of system level thermal design involves proposing system cooling strategies, which ensure that the system design objectives are met within the constraints imposed by Bellcore GR-63-CORE.

Recirculation Design - Overview

Primitive flow network models of conventional cooling schemes showed that a novel strategy was required to meet the required target slot air velocities and the required allowable air temperature rise. Figure 2 illustrates the basic principle of the partial recirculation system. Air is drawn in through the intake baffle and through the air filter. It then mixes with warmed air that has passed over the I/O section. This mixed air passes over the line cards and through the cooling units. It is then either exhausted out of the shelf through the front and rear exhaust baffles or is directed up through the I/O section. The partial recirculation scheme results in higher air velocities over the circuit cards than would be possible if a non-recirculation scheme was employed.

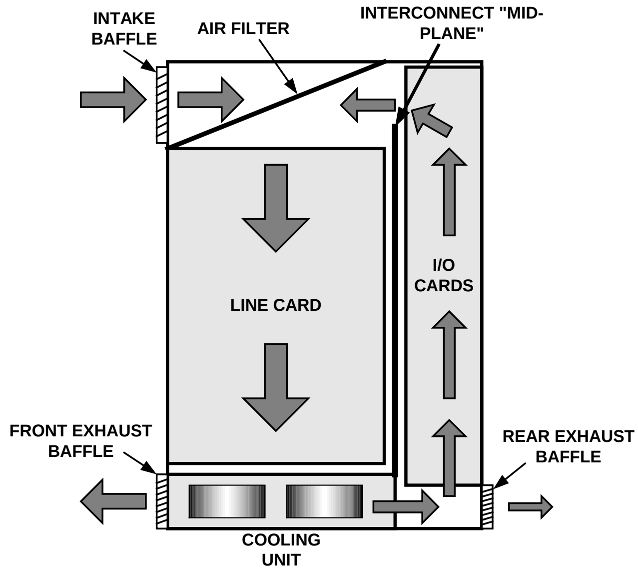

Figure 2. Partial Recirculation Cooling System

MODELING METHODOLOGY

Primitive Modeling Phase

The airflow architecture was modeled using MacroFlow. Initial models were primitive, utilizing manufacturer's data for fan curves and filter resistance, and educated guesses for flow resistances through the card slots. The purpose of these primitive models was to validate the feasibility of the proposed airflow architecture before investing more intensive R&D effort. Figure 3 shows the extent of a primitive model superimposed over the block diagram of the airflow architecture.

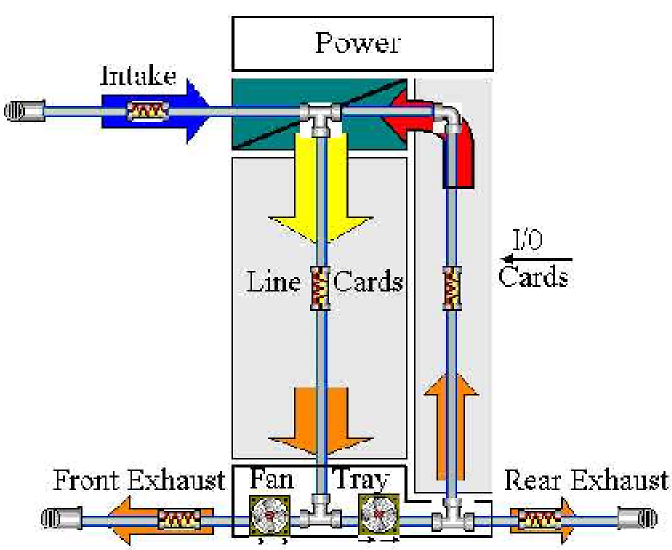

Figure 3. Primitive Flow Network Model of 7670 50 Gig

Development Modeling Phase

Following primitive modeling, further details were added to the MacroFlow model as more accurate information on system components became available. Building full size mockups of components and testing them on an Airflow Test Chamber (figure 1) generated much of the detailed data used. Piecewise linear data from these tests were entered directly into the properties of the components in the Flow Network Model, replacing the estimations entered in the primitive model phase. A key element in this phase was to replace the manufacturer's fan curve with a 'fan tray' curve that incorporated all losses due to metalwork proximity and flow turbulence caused by close spacing of multiple fans.

Final Modeling Phase

As the detailed mechanical design became available, the MacroFlow model in Figure 3 was further enhanced. Details such as PCB stiffeners were incorporated into the card slot models, and as the Hardware design evolved, knowledge of the presence of daughter cards allowed further improvements to the definition of the card slots. Figure 4 shows an example of the enhanced card slot model. As prototype mechanical parts such as plastic intake and exhaust louvers arrived, accurate component resistance data was measured and entered into the model. Detailed air filter data was entered and a transient solve was performed to predict the effects of dust loading on system performance, leading to determining filter change intervals for a given installed environment.

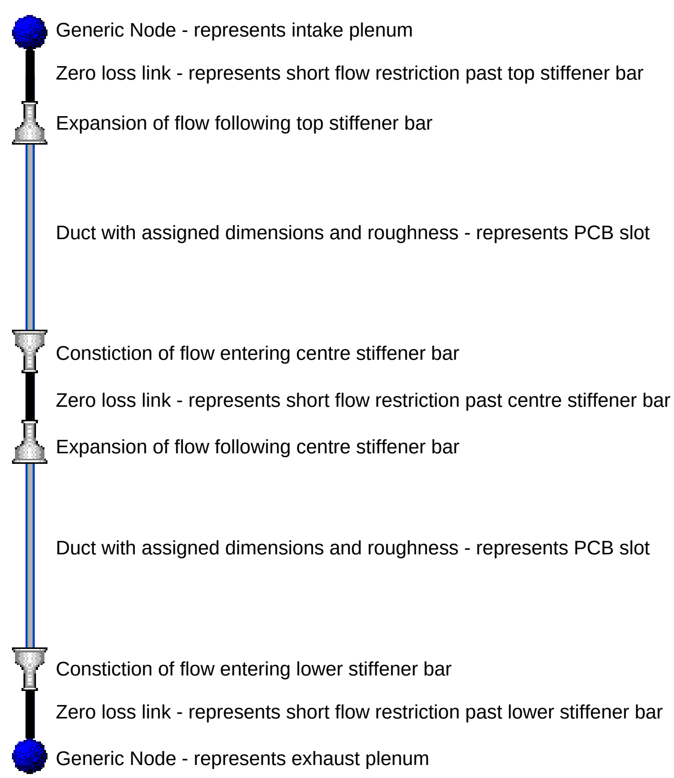

Figure 4. Enhanced Card Slot Model.

MODEL RESULTS

Model Limitations

Since the one-dimensional Flow Network Model cannot portray the inter-relationship of closely spaced fans and their associated mixing plenum below the card cage, the flow distribution between card slots is limited to the effects of their respective flow resistances. As such, the card slots were treated in a bulk manner and analyzed only for volumetric flow and velocity. Similarly, heat load can only be entered as a bulk quantity as opposed to modeling individual components on a PCB, so for the sake of simplicity and speed, the heat transfer option was turned off and the model was solved only for airflow properties.

Bulk Flow Model Results

The partial recirculation airflow architecture of the model necessitates treating bulk airflow and internal air velocity separately. The model was solved for volumetric flow rates at the inlet to the fans (location C in Figure 7) and the recirculation duct (location F in Figure 7). A transient MacroFlow model using a time dependent filter correlation was run to simulate clogging the air filter with an air quality environment per NEBS [1]. Values for clean and dirty air filter modes are presented. There were no experimental results for the dirty filter condition.

Table 2: Bulk Flow Model Results

LOCATION	CLEAN AIR FILTER	DIRTY AIR FILTER
Fan Inlet (Location C in Fig 7)	780 CFM	750 CFM
Recirculation Duct (Position F in Fig 7)	269 CFM	301 CFM

Air Velocity Model Results

Air velocity was solved for each type of card slot present in the system. Due to mechanical design constraints, the card slots at each edge of the shelf were different from the internal slots. These differences were present in both the front 'line' slots and the rear 'I/O' slots, resulting in a total of four slot types requiring analysis (Table 3). Values for clean and dirty air filter modes are presented.

Table 3: Air Velocity Model Results

SLOT TYPE	CLEAN AIR FILTER	DIRTY AIR FILTER
Line Edge	2.55 m/s	2.47 m/s
Line	2.49 m/s	2.39 m/s
I/O Edge	2.64 m/s	2.94 m/s
I/O	2.51 m/s	2.80 m/s

DESIGN & TEST METHODS

Bulk Flow Measurements

The airflow within the 7670 50 Gig system is represented by the arrows in figure 5. Air is drawn in through the intake and air filter. It then mixes with warmed air that has passed over the I/O section. This air passes over the line cards and through the cooling units. It is then either exhausted out of the shelf or directed up through the I/O section.

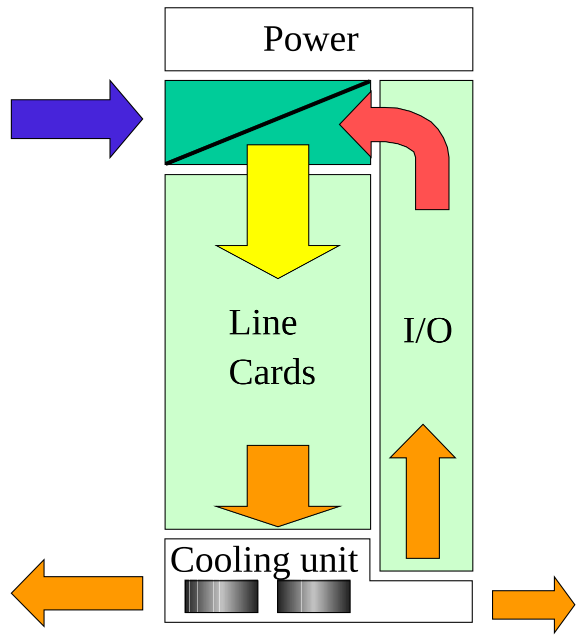

Figure 5. Direction of Flow in 50 Gig System.

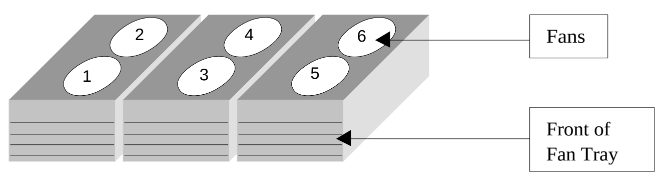

Figure 6: Fan and HWA probe numbering.

Shelf Flow Rate Measurements

The bulk flow measurements performed on the 7670 50 Gig system differ from typical telecoms enclosures because of the recirculation of air within the shelf shown in Figure 5. In order to determine the volumetric flow rate of air through the fans, Hot Wire Anemometer (HWA) probes were placed at the inlet to each of the fans. The fans and the corresponding probes were numbered according to Figure 6.

The system under test was forced to exhaust all of the air passing through the fans by blocking off the recirculation slot located at the top of the midplane. By capturing both the exhaust and the leakage out of the I/O section with two Airflow Test Chambers (obstruction type flow meters), the total volumetric flow passing through the fans was determined. A relationship between the volumetric flow rate through the fans and the velocity recorded by the HWA airflow probes was thus established.

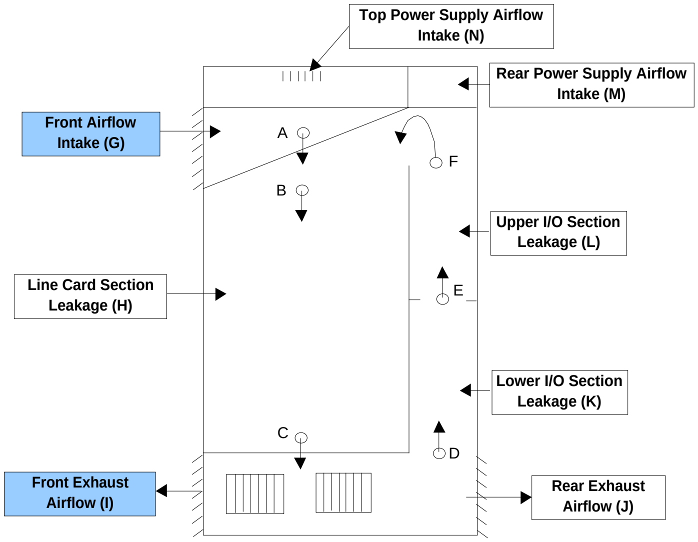

Figure 7. Overview of system showing various volumetric flows

The velocities captured by the third and fourth probes (v3 and v4) were found to be the most linear throughout the various volumetric flows. The experimentally determined correlation between the measured air flows and the measured velocities was:

Volumetric Flow (cfm) = v3 * 76.247
Volumetric Flow (cfm) = v4 * 90.372

Once the above test was completed, the recirculation blockage was removed and the system was allowed to operate normally. The intake was connected to one airflow chamber and the 2 exhausts (front and rear) were connected to another airflow chamber. A difference in volumetric flow was noted between the two chambers, proving that leakage (through gaps between the faceplates of adjacent circuit cards) was significant. Individual sections of the system were then run through a third, smaller airflow chamber to determine the various leaks in the system. The results are presented in Table 4.

Table 4: Volumetric Airflow Rates

Location (Figure 7)	Volumetric Flow (Cubic Feet Per Minute)
A	462
B	678
C	734
D	194
E	201
F	216
G	399
H	56
I	351
J	189
K	7
L	15
M	23
N	40

The average air velocity at each location in the shelf was determined by dividing the bulk flow by the effective cross sectional area of the section. The cross section is taken as the width times the depth minus the area of the cards. For the line cards, the effective depth was taken between the metal stiffeners. In the I/O section, the effective depth was taken as the distance between the faceplate and the midplane connectors that block most of the flow near the midplane. The average velocities occurring in the shelf are presented in Table 5.

Table 5: Average Velocities based on Bulk Flow

Location	Slot Velocity (m/s)
B	2.5
C	2.7
D	2.5
E	2.6
F	2.8

COMPARISON: MODELED & MEASURED RESULTS

Tables 6 and 7 present the comparison between the modeled and measured results. Since all lab measurements were performed using a clean air filter, the corresponding clean air filter model results are used for comparison.

The results show a very close agreement between the predicted and measured results, with the exception of the recirculation bulk flow rate, which shows a difference of 24%. A much higher than anticipated density of power cables routed across the recirculation duct was attributed to this error. A corresponding difference in the I/O slot velocity does not appear as the final effective cross sectional area of the I/O slots differed from that used in the model.

Average measured slot velocities were used for comparison data to the model values, as the scope of the model was limited to bulk flow values and not flow distribution. Average line card velocity was obtained from the values of B and C in Table 5. Average I/O card velocity was obtained from the values of D, E and F in Table 5.

The airflow performance of the telecom shelf met the design objectives with margin. Line card and I/O card air velocities were above target levels, and bulk airflow transfer resulted in a theoretical air temperature rise in the system of 18°C at designed maximum conditions.

Table 6: Comparison of Final Model Predictions & Measured AirFlow Rates

LOCATION	CLEAN AIR FILTER MODEL	MEASURED BULK FLOW	% DIFFERENCE
Fan Inlet (Location C in Fig 7)	780 CFM	734 CFM	6 %
Recirculation Duct (Location F in Fig 7)	269 CFM	216 CFM	24 %

Table 7: Comparison of Predicted & Measured Air Velocities

SLOT TYPE	CLEAN AIR FILTER MODEL	AVERAGE MEASURED SLOT VELOCITY	% DIFFERENCE
Line	2.5 m/s	2.6 m/s	4 %
I/O	2.5 m/s	2.6 m/s	4 %

CONCLUSIONS

The use of Flow Network Modeling in conjuction with the ability to measure element performance using an obstruction type flow meter enabled the design of a novel partial recirculation cooling scheme for a high power telecoms shelf. Comparison of the measured and modeled data shows that there is a very close agreement in bulk flow prediction except for the recirculation bulk flow rate, and that difference was due to a much higher than anticipated density of power cables routed across the recirculation duct.

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