A Study on the Effects of Unwanted Air Infiltration on Thermal Comfort at an Airport Terminal

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ABSTRACT

The Energy Systems Laboratory at Texas A&M University is currently studying ways to make improvements in thermal comfort at the Terminal E building at DFW airport. Airport terminal building HVAC systems are generally known to consume large amounts of energy to provide an environment that is comfortable for the employees and travelers. Wind direction, the shape and orientation of the building with respect to the prevailing wind can have a deleterious effect on the HVAC system ability to provide the comfort levels that people have become accustomed to in public buildings. Airport terminal buildings, such as the one in this study, built before the current energy awareness that is prevalent today have many problems associated with air infiltration primarily due to openings in the building structure to permit a smooth flow of passengers and luggage toward their destination. Entry ways that allow for easy egress generally use sliding door vestibules that are self closing based on sensors and timers to provide the building user an unimpeded path into and out of the building. During peak traffic periods, these doors are open for relatively long periods of time and can cause significant loss of building pressure. If the shape of the terminal building is such that the gate doors to the aircraft are opposing the egress entryways, air flows can develop within the building that blow across the width of the building, causing drafts that can either be cold or hot based on the outside air temperature. The shape of the building in this study is C-shaped with the opening of the "C" facing toward the West. Weather data will be analyzed along with hot and cold calls within the terminal building to correlate the effect of wind direction on indoor thermal comfort. Unwanted air infiltration flow pathways will be identified using smoke testers and analyzed with efforts to reduce entry into the building envelope

INTRODUCTION

Airport terminal building HVAC systems are generally known to consume large amounts of energy to provide an environment that is comfortable for the employees and travelers. Wind direction and the shape and orientation of the building with respect to the prevailing wind can have a deleterious effect on the HVAC system ability to provide the comfort levels that people have become accustomed to in public buildings. Airport terminal buildings, such as the one in this study, built before the current energy awareness that is prevalent today have many problems associated with air infiltration primarily due to openings in the building structure to permit a smooth flow of passengers and luggage toward their destination. Entry ways that allow for easy egress generally use sliding door vestibules that are self closing based on sensors and timers to provide the building user an unimpeded path into and out of the building. During peak traffic periods, these doors are open for relatively long periods of time and can cause significant loss of building pressure. If the shape of the terminal building is such that the gate doors to the aircraft are opposing the egress entryways, as is the case for DFW Terminal E, air flows can develop within the building that blow across the width of the building, causing drafts that can either be cold or hot based on the outside air temperature. The shape of the building in this study is C-shaped with the opening of the "C" facing toward the West. Weather data will be analyzed and compared with hot and cold calls within the terminal building to correlate the effect of wind direction on indoor thermal comfort. Unwanted air infiltration flow pathways will be identified using smoke testers and analyzed with efforts to reduce entry into the building envelope.

Terminal Eis one of four C-shaped terminal buildings at DFW International airport with 27 jet bridge gates leading out to aircraft. At the time the terminal was constructed in the early 1970's, it was considered to be a state-of-the-art building designed to permit ease of passenger flow from the street through the terminal and onto waiting aircraft without much delay. The early 1970's was also a time when fuel was in abundance and prices were low, so not much attention was paid to HVAC efficiency. It was occupied primarily by Delta Air Lines until Delta closed its hub in 2005 at DFW and has recently begun serving Delta again along with several other carriers. After the September 11, 2001 attacks on the United States, increased security requirements mandated changes at the terminal to only permit ticketed passengers access to the gate areas on the now secure side of the building. These changes effectively divided the terminal down the center of the C shape and closed off high ceiling corridors that were part of the original architecture design that permitted free movement of people and air throughout the terminal building. These corridor areas were walled in with glass down to a ten foot height and are now serving as Transportation Safety Administration (TSA) security checkpoints for outbound passengers or to provide passage of incoming passengers access through revolving doors to baggage claim carousels on the non-secure side. The terminal has a total of four security checkpoints that are, in most part, directly in-line with the entryways to the non-secure side of building and the gate doors leading to aircraft through jet bridges. These four areas have the majority of hot and cold complaints. The terminal has a currently unused satellite building that is connected to the main terminal by an underground tunnel. Terminal E is also connected to other terminals by an automated people mover called the Skylink that was dedicated in 2005 and added two station towers on the East side of the building that are each 50 ft in height, 25 ft wide and 100 ft long at the very top. Escalators deliver passengers to and from the elevated platform serve from and semi-circular additions to the main terminal building. Two stations at the top of the tower are served by automated trains running in both directions arriving at each station about every three minutes during the main business hours and every ten minutes after 12 PM. There are two sliding access doors per train. The total terminal square footage is approximately 781,000 sq ft, not including the satellite building.

INCREASING BUILDING PRESSURE TO REDUCE INFILTRATION

Our main focus at ESL for many of our customers during the Continuous Commissioning® (CC®) projects is to reduce the energy consumption of HVAC systems. For DFW airport Terminal E our main focus is to investigate the cause of comfort problems, and identify ways to improve overall thermal comfort for passengers, tenants and employees and reduce the number of hot and cold calls coming into the maintenance provider. Our work should also help reduce overall energy consumption at the same time. The focus of this paper will be dedicated to the discovery of issues affecting thermal comfort and findings related to our investigative work.

The initial approach to overcoming thermal comfort issue is laid out here as part of the design of experiment:

- Review the comfort complaints
- It was known that outside air dampers were not open on most of the AHUs
- 0.05 inches of water was set as the lowest acceptable value for building static pressure
- Record baseline building static pressure readings at entry ways
- Analyze the data to determine if the building is being pressurized
- Based on pressure data being negative, verify that outside air dampers are open to increase building pressure
- Record building pressure again at the same location as the baseline
- Compare readings to see if building pressure increases

The result of the experiment showed no significant increase in building pressure, with most readings remaining negative. The next step in our design of experiment was to measure the amount of outside air at the intake point to obtain a better value of the total outside air. It was discovered that several AHUs had balance dampers within the outside air duct that was pinched down and restricting the flow.

All of these dampers were opened to maximize outside air intake and flow measurements were taken. The average percentage of outside air to total supply air was found to be 20%. Physical measurements of the air intakes on the mechanical room roofs showed that the overall square footage of the outside air duct was larger than the inlet vane cross-section area. One roof cap for AHU #1 was removed and intake duct CFM readings were retaken and a 33% increase was realized. Because of the number of roof caps that would have removed to increase flow, we decided to take another approach to increasing outside air to the AHUs, and opened access doors on each unit between the return air and the filter. The doors were about the same size as the roof cap. Another set of building pressure reading were taken at the A section of the terminal. The readings improved slightly toward a neutral pressure, but not to the goal we had set of 0.05” WC. At this point, we started to search deeper into the reason for negative building pressures in sections A and B of the building and positive pressure in section C.

Table 1 Terminal E Building Pressure Readings

		5/12/2009 AM prior to commanding OA dampers to 100% for AHUs in A&B sections	5/12/2009 PM after commanding OA dampers to 100% for AHUs in A&B sections	05/14/09, 5.00 PM, OA Dampers open in all sections	05/26/09, 10.06 am, OA Dampers open in all sections	Change from initial to final readings by Section, Avg
Section	**Location**	**Building Static inches of H2O**	**Building Static inches of H2O**	**Building Static inches of H2O**	**Building Static inches of H2O**	**Building Static inches of H2O**
C	Sliding door UL E35	0.052	-0.044		-0.002	-0.064
	LL E35 Sliding door	0.08		0.045	-0.003	
	Sliding door UL E33	0.051	-0.072	0.032	-0.018	
	LL E33 Sliding door	0.044			-0.013	
	Sliding Door, 4 E 131	0.04		0.025	0	
	UL E31 Sliding door	0.08	-0.039	0.03	-0.023	
	LL E31 Sliding door	0.029			-0.014	
B	UL Door E17	0	0	0.015	-0.008	0.001
	LL Sliding Door E17		0.03		-0.008	
	LL E16 Sliding door (exit only)	0.015	0.002		-	
	LL E16 Sliding door	0			-0.011	
	Door UL E16	-0.03	0.011	0.014	-0.01	
	LL E15 Sliding door	-0.006	0.035		-0.014	
	Door UL E15	-0.03	0.036	0	-0.014	
	Door UL E 14	-0.022	0.028	0	0	
	LL E11 Sliding door	-0.008	-0.02		0	0.008
A	Door UL E8	-0.007	0.0106	0	-0.022	0.019
	LL E8 Sliding door	-0.007	-0.015		0	
	Door UL E7	-0.018		-0.01	0.006	
	LL E7 Sliding door	-0.007	-0.011		0.005	
	Door UL E5	-0.01	-0.008	0	0.009	
	LL E5 Sliding door	-0.03	-0.004		0.004	
	Door UL E3	-0.001	-0.003	0	0.06	
	LL E3 Sliding door	-0.009	-0.002		0	

While walking the length of the terminal searching for sources affecting the building pressure imbalance, we noticed that between sections A and B, and between B and C, there was quite an amount of air flowing between the sections where the cross section of the building narrows. Airflow measurements in these areas were taken at several points along the “hallway’ and recorded. The maximum airflow velocity reading was 450 ft per minute and the lowest was 350 ft per minute.

ESTIMATING AIR INFILTRATION

Calculating a good estimate of air infiltration into and out of the terminal would be a nearly impossible task because of the large number of known and the unknown or undiscovered pathways. For the purposes of this project and to provide our customer with a more scientific approach to the estimated amount of air infiltration, a calculation using certain known sources is warranted.

Data collected by DFW airport for terminal E and published on the airport website, provided information on the number of passengers enplaning and deplaning each month. This information combined with equation (53) shown below and published on page 16.27 of the 2009 ASHRAE handbook was used to calculate an estimate of average infiltration rate through the automatic doors leading to the building. The passenger data spanned a 5 month period from January 2009 through May 2009 and was used to compute an average number of passengers on an hourly basis using 18 hours of daily terminal operation as the devisor. This average was then used as an input to determine the airflow coefficient for automatic doors with vestibules. Terminal E has a total of twelve double door entry ways leading to the non-secure side of the building, all with vestibules, and a total of 26 airline gates that are open for at least 45 minutes each during boarding and deplaning. Doors at the bottom of escalators leading outside on the lower level also have vestibules, but they are not used as extensively as the upper level doors and therefore were not considered in the airflow calculation. Pressure data collected at each of the entry points, and shown in Table 1 above, will be used as the Δp value in calculating the total estimated loss through the entry doors.

From the DFW data the average number of people using the doors was calculated to be 80/hour, and then using the air coefficient chart, C_A was found to be 200. A value of 42 ft^2 was used as the cross sectional area for each automatic door.

The total airflow estimate was calculated using the following:

$$Q=C_A A \Delta p^{1/2}$$

Where

Q = airflow rate, cfm

C_A = airflow coefficient from ASHRAE 2009 fig, 16, pg 16.26, cfm/[ft^2 (in. water)$^{0.5}$]

A = area of door opening, ft^2

Δp = pressure difference across door, in. of water

The total from the data approximates 190,000 cfm airflow across the twelve entry way doors. If the same number of people using the entry way doors also used the jet bridge/gate doors (21 ft^2), then it is safe to assume that the actual airflow is 1.5 times 190,000, or 285,000 cfm for the terminal. Since the pressure across the doors was measured to be negative, the airflow outward and a loss to the system.

Comparing the airflow value above to the combined measured value of outside air intake at the air handlers, the only time the building has a chance of becoming pressurized is during the night hours when the airlines have no flights. Unfortunately, being able to pressurize the building at night will have no impact on thermal comfort during normal operating hours.

HOT AND COLD SPOTS

DFW terminal management reported that the areas around the security checkpoints had the highest occurrences of hot and cold calls to the maintenance department. The maintenance department captures the call in a work order data base and has an HVAC technician address the complaint. The process to address the complaint depends on the technician that is given the work order and their experience level in dealing with the complaints. ESL requested a data dump of the work orders related to either hot or cold complaints to attempt to identify the root cause of the complaints. ESL reviewed and compiled the data to remove any unrelated information and categorized the complaints into figures 1 and 2 below. The data shows that a large majority of complaints occur at or around the TSA checkpoints where passengers are waiting in line, or employees are stationary. The chart also shows a high number of calls at the center of the building's C-shape and where entryways line-up with the checkpoints and gate doors on the opposite side of the building. ESL performed another walkthrough of the area with high complaints and noticed a large amount of air movement during those times of high passenger traffic and gate doors being opened. The gate doors are typically open for one-half hour before the aircraft departure time to allow boarding.

Further analysis of the hot and cold call data was performed along with wind speed and direction data from NOAA. When the data from hot and cold complaints was compared to the wind data, it became very evident that weather conditions were having a dramatic effect on indoor thermal comfort.

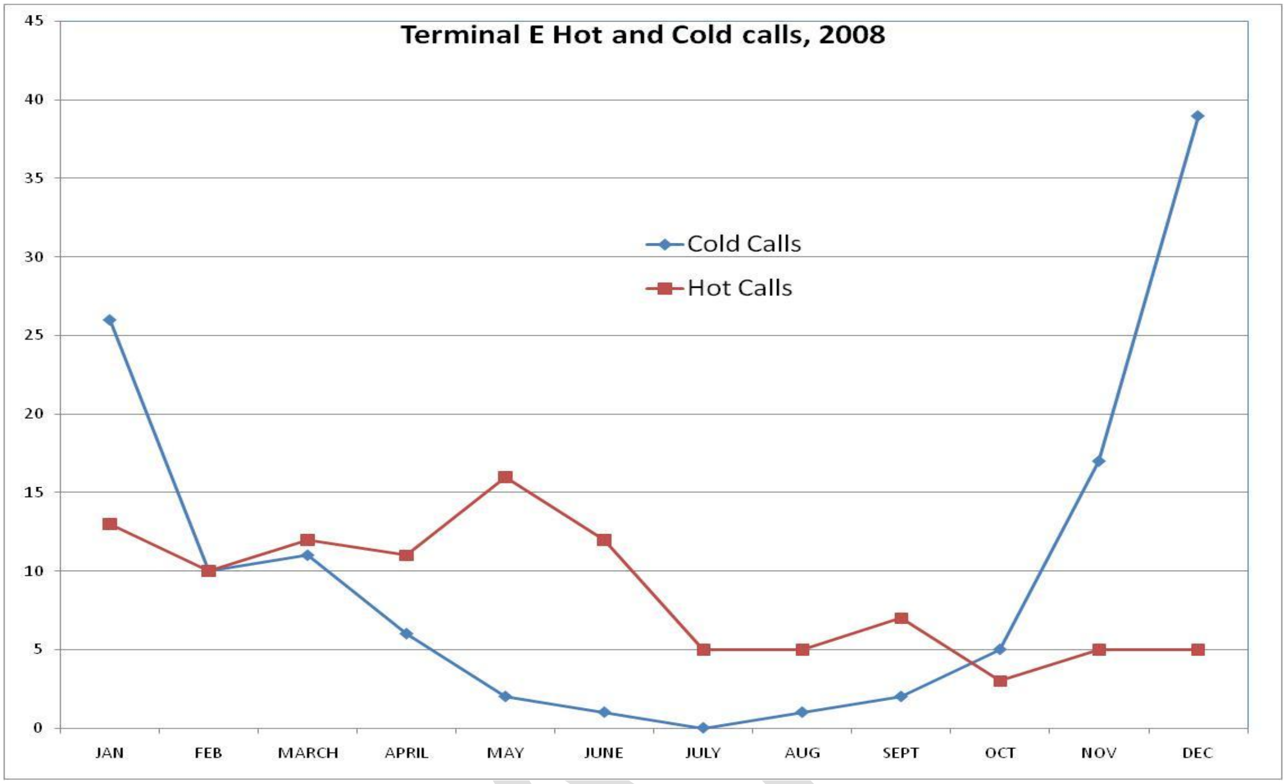

Figure 1 **Terminal E Hot and Cold Calls**

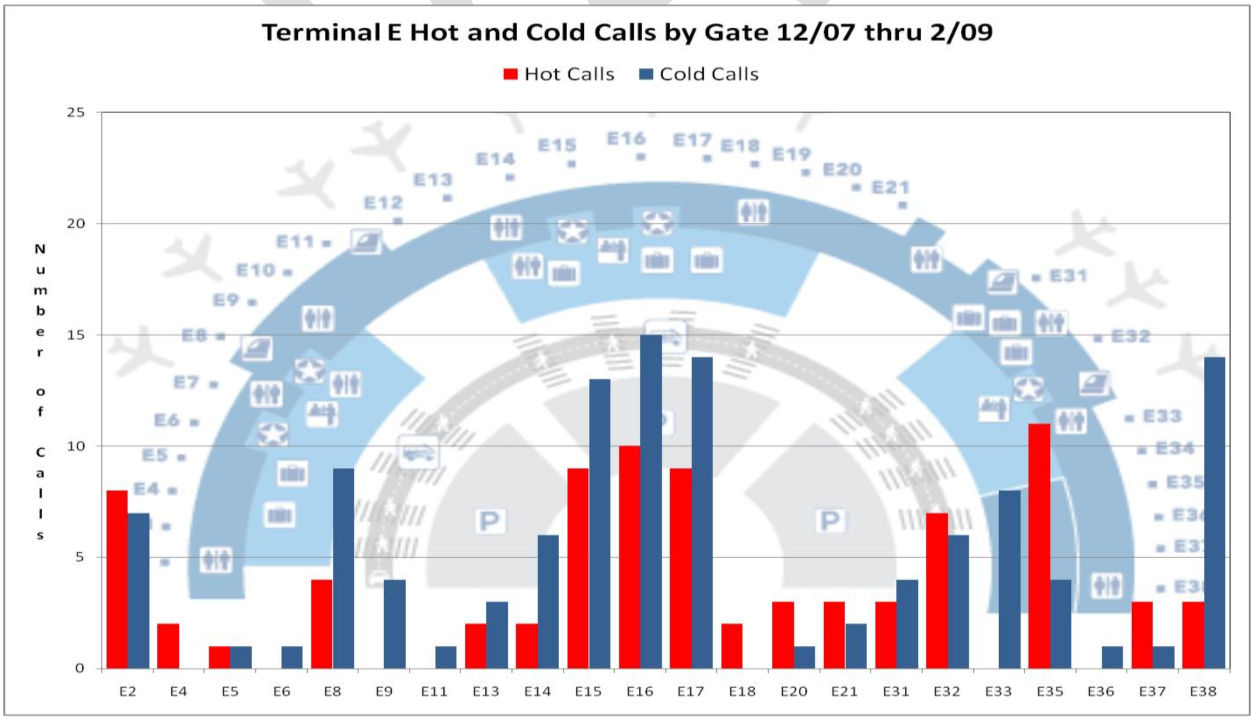

Figure 2 **Terminal E Hot and Cold Areas**

WIND EFFECT ON BUILDING PRESSURE

Before the effort to increase building static pressure by increasing the amount of outdoor air being drawn in by the HVAC systems, section C of the terminal building had a positive static pressure reading. After opening the outside air dampers completely, the static pressure relative to outside in section C decreased. Although there was a drop in static pressure in section C, the doors leading to the outside at the Southwest side of the building had a pronounced movement of air flowing out of the door when opened, indicating a positive static pressure. Table 1 shows a difference in static pressure for section C from positive to negative on different days when building pressure readings were taken. This difference in pressure was significant enough and led the team to investigate for possible air infiltration points and to compare weather conditions on the specific days when the readings were taken. Weather data for the days reading were taken were reviewed and it was revealed that when the wind was out of the South-Southeast, the static pressure in section C of the terminal was positive and when the wind was more out of the northerly direction the static pressure was lower or negative with respect to the outside pressure.

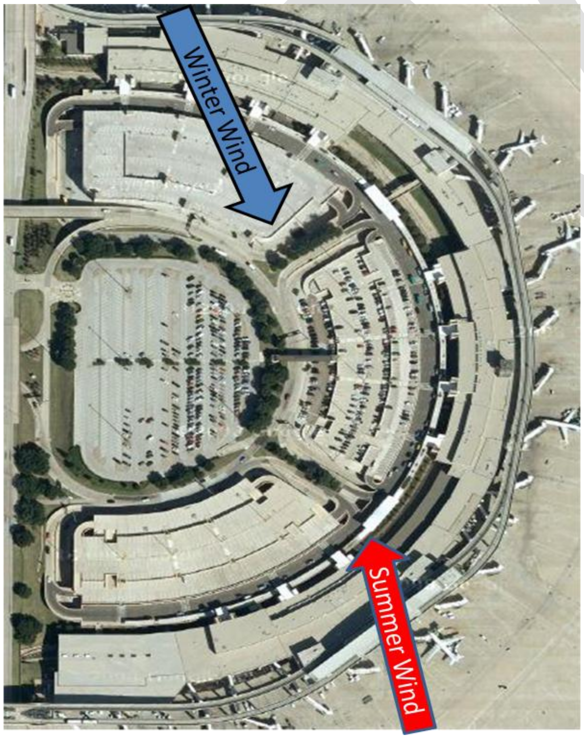

Figure 3 Seasonal Prevailing Wind

Wind driven air infiltration can also have a dramatic effect on internal building static pressures. The wind speed and direction with respect to the building and pathways for infiltration can cause pressure differentials that cause migration of internal air from high to low pressure areas. Wind pressure or velocity head values for various wind speeds were derived by the Bernoulli equation and tabulated below:

$P_w = 0.0129\ C_p \quad U^2/2$

Where

P_w = wind surface pressure relative to outdoor static pressure in undisturbed flow, in. of water

ρ = outside air density, lb_m/ft^3 (about 0.075 at or about sea level)

U = wind speed, mph

C_p = wind surface pressure coefficient (scalar)

0.0129 = unit conversion factor, (in. of water)· ft^3/lb_m ·· mph^2

Table 2 Indoor Static Pressure due to Wind Speed

Wind Speed (MPH)	Velocity Pressure (in. of Water)
Table 3 Indoor Static Pressure due to Wind Speed **10**	0.05
15	0.11
20	0.20
25	0.30
30	0.44

The building shape, height and architecture can affect indoor building pressure either in the positive or negative direction. Generally the windward side of the building will exhibit the more positive pressure and the leeward side a negative value. Because of the terminal building having a C-shape at some point along the outside of the C, a neutral point will exist where the pressures are equal and could produce false positive or negative readings. Therefore it is important to consider building size shape, the number and size of infiltration points, and orientation to the wind when attempting to establish baseline building pressure readings. Emphasis on removing or reducing the infiltration points and sources is recommended.

AIR INFILTRATION SOURCES

The search for possible sources of air infiltration into the terminal building was done by performing a walkthrough of the entire interior and exterior of the building including the tarmac/ramp area on the secure side. The following is a list of the findings:

- Entry way vestibules into the building from the upper street are only 12 feet in length. The short length causes both the outside and inside sliding doors to be open simultaneously.
- Sliding doors on the lower level were found to be inoperative and open 100% of the time.
- A few Gate doors to jet bridges were being left open to the terminal.
- Several doors at the airplane end of jet bridges were open.
- One gate called "The Breezeway" had a large amount of air flow through the terminal because it is in-line with the security checkpoint and the outside entry.
- Two large exhaust fans are pulling air out of the terminal through electrical switchgear rooms.
- One switchgear room had a hole in the masonry wall at the top and a definite draft was felt. Further investigation showed a direct path to the concourse below the suspended ceiling tiles.
- Exhaust hoods from food concessions in the terminal with broken make-up air units.
- Many penetrations exist into air conditioned space from pipes, drains and exhaust fans.
- The terminal has ten baggage carousels that deliver bags from the ramp level (which is exposed to the outside air and wind) to the no-secure side of the terminal. Each baggage carousel has an associated conveyor belt that penetrates the floor to the ramp. Upon investigation, it was found that the space around the conveyors had not been enclosed to prevent air infiltration to the space under the carousels. Smoke test confirmed the air coming into the concourse at one of the carousels.
- The terminal also has numerous out-bound conveyors for passenger baggage at ticket counters that have also have not been enclosed.
- The wind, when out of the South East or East also amplifies the infiltration through the baggage carousels on the South end of the terminal.
- The addition of the two Skylink tower stations has added a significant potential for a stack effect.
- The Skylink stations have sliding doors that open to both the East and West side of the tower every three minutes during the day and every ten minutes during late night hours.
- The East side of the terminal building (the closed side of the C) is open to the runway and has no wind break. The predominant wind direction during summer months is from the South East.
- The wind speed and direction creates pressure differentials with the building and from side to side.
- When the wind is out of the North or South, a neutral point for wind pressure is at the center of the semi-circle of the c-shaped building, where most of the hot and cold complaints come from.

At this point, with a relatively large number of infiltration points identified, the process of convincing our customer that these are really having a drastic effect on thermal comfort had to be devised.

Smoke Test

A small scale smoke test was conducted within the terminal building to determine the sources and pathways of the airflow and to provide a visual means of showing the air currents within the terminal. The test was conducted after midnight when people traffic throughout the terminal was at a minimum. A small hand-held air current kit that puts out puffs of smoke was chosen to prevent setting off smoke detection devices. Areas that were known to have hot and cold complaints were tested first, especially the security checkpoints with doors on either side leading outside. Gate number 16 has the most direct pathway for air to flow through the terminal. Entry way doors on the terminal non-secure side were opened simultaneously with jet bridge doors on the opposite side of the building. The smoker was activated and held near the door leading to the jet bridge and the tarmac. The effect was quite visible and flow readings of 480 ft per minute were recorded using a hot wire anemometer. Weather conditions at the time of testing were: temp 84°F, Wind, SSE at 15 mph with 17 mph gusts, and RH of 47%. The location of the test in the terminal is in the center of the C-shaped terminal building. The schematic below shows the layout of the terminal at the test point and general airflow path.

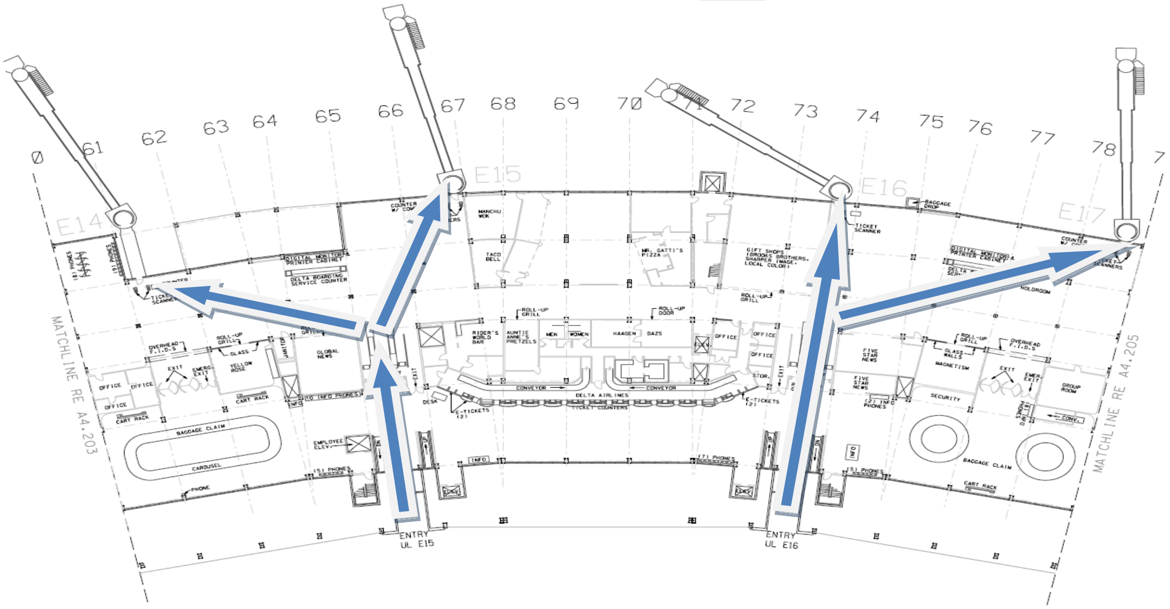

Figure 3 Airflow through Terminal E

It is known that wind forces act on buildings creating positive pressure on the windward side and a negative pressure on the leeward side. Eighteen months of weather data from the NOAA archive was analyzed for wind prevailing direction at DFW airport. Figure 3 shows the general wind direction during the summer and winter months. Spring and autumn seasons in the Dallas area tend to be short, and the wind direction for spring is similar to that of summer and likewise for winter and fall. During the smoke test, it was noticed that certain areas within the terminal had air movements much higher than others. The areas with the higher air motion were much narrower than the open waiting and seating spaces near or around gate doors. Air movement velocities of 350 to 450 feet per minute were recorded in the narrow passages between sections C-B, and B-A, with the direction of the air movement toward the North end of the building.

The spaces with the greatest air movement are also located near the Skylink terminals that were added to the building in 2005 and have HVAC air handling units separate from those in the main terminal building. Smoke testing in these areas showed a definite air movement pattern coming from the area where the Skylink stations are located toward the main terminal and through the narrow passages, with the air flow moving from South to North.

Areas in the vicinity of the terminal's ten baggage claim carousels were examined and several clues to air infiltration were observed. Several HVAC diffuser vents had drops of condensation on the outside, and in a few cases the humidity has been so high that ceiling tiles were sagging, and air currents could be felt on the skin. Smoke tests conducted around baggage claim areas 37 & 38 confirmed that air infiltration was taking place and at rate large enough to give a false sense of positive building pressure at entry way doors nearby. A logger was installed to measure temperature and humidity and the output is shown in fig. 5.

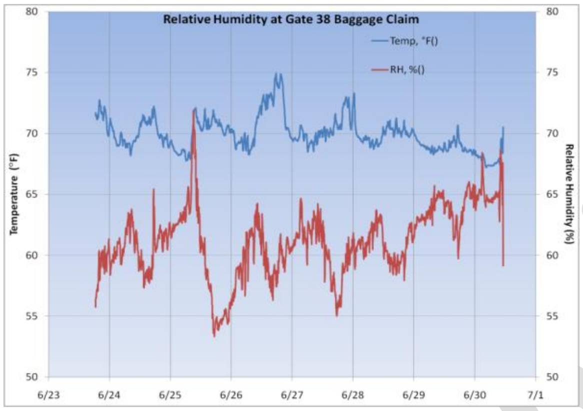

Figure 4 Baggage Claim Area Humidity

THE STACK EFFECT

In 2005 DFW airport added an automated people mover called the Skylink, to give passengers the ability to transfer between terminal buildings without leaving the TSA security area. Each terminal has two Skylink station towers measured from the concourse level at 50 feet in height, 35 ft wide, and 120 ft long. The train platforms are 30 feet above the concourse and are accessed via three escalators on each end of the platform. The escalators are open to the main concourse below with no separation of the two spaces. Two trains go in opposite directions and arrive at each terminal station about every two minutes during peak times and every ten minutes from midnight to 5:00AM. Two automatic double doors lead to each train. At times, two trains are present at the station on opposite side of the tower with doors open. The towers are on a separate HVAC system that does not communicate with the main terminal system. During the smoke test, there was a visual confirmation of airflow into the terminal building and coming from the two Skylink terminals. The pressure differential causing the airflow is related to the stack/chimney effect. Building pressure set point in the building automation system controls is .08 in. of water. Records show that the measured building pressure in the Skylink is typically .01” to a negative value based on the time of day, wind speed and direction. During the night time hours, two exhaust fans at the top of the towers could draw air out of the building if the building pressure exceeds 0.08”. Trending of the fans is not possible at this time. Further study of the Skylink stations is warranted, but due to the number of variables associated with the building configuration, weather conditions and intermittent door openings a true stack effect calculation and the ultimate effect on airflow in the terminal building may not be achieved.

RECOMMENDATIONS

Observations regarding air infiltration and air movement within the terminal during this study have led to the following recommendations:

- Install glass partitions with sliding between sections of terminal to reduce the natural air migration from South to North.
- Install revolving doors at entry points that are large enough to handle passengers and baggage.
- Install glass wall partitions in the areas with the greatest amount of hot an d cold call complaints (this will not stop air infiltration, but will redirect drafts).
- Replace current air curtains with units that are more efficient.
- Reduce the overall number of entry ways to those most used (will need to study traffic patterns)
- Enclose baggage carousel conveyors with drywall enclosures that are taped and sealed to the floor to provide an air barrier.
- Repair or replace any broken make-up air units for terminal concessions.
- Lengthen the existing vestibules to 24 ft and set the sensors to close the rear doors sooner but not less than the ADA recommendations.

The strategy here is to address the big, easy-to-fix, air- infiltration items first, evaluate the impact and then move on down the list while keeping an eye on the cost to fix versus the benefit of lowering or removing the leakage points.

CONCLUSIONS

Maximizing thermal comfort in an indoor environment such as airport terminal buildings is difficult due to the inherent nature of the building itself. The terminal is primarily used for the conveyance of passengers and baggage through the building and onto the aircraft and onward to their final destination. In order to optimize this conveyance, the building has many openings that also permits air to infiltrate into the interior and escape outward, and in some cases the openings provide a direct pathway for air to flow completely through the building unimpeded. Weather caused air infiltration such as wind speed and direction and the effect on building pressure, or the stack effect caused by inside and outside temperature differences are mostly uncontrollable and constantly change. Improvements in thermal comfort for the terminal patrons and employees can be accomplished by implementing controls on air infiltration, but cannot be completely resolved without a large capital outlay.

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