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AIR CURTAIN PERFORMANCE STUDIES IN OPEN VERTICAL REFRIGERATED DISPLAY CASES

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Abstract

Air curtains in open refrigerated vertical display cases are designed for creating an invisible barrier between the cold air inside and the warm air outside of the case. A modular display case is built to allow the variation of flow and geometrical parameters. This unit is used 1) to directly measure the infiltration rate as a function of all of these parameters by using a tracer gas, and 2) to understand the fluid dynamics of the air curtain, by using Particle Image Velocimetry (PIV) technique. Based on this study, an artificial neural network (ANN) program was developed that assisted the researchers in specifying those flow parameters and geometrical configurations that minimized the infiltration rate, and the cooling load thereafter. A display case, based on these design specifications, was fabricated and tested. A 13 percent reduction in the infiltration rate was produced which translates into $200 M savings, and approximately 0.5 M tons of reduction in green house gases in the United States. The temperature of the food was also monitored, and in all cases met the Food and Drug Administration (FDA) requirements. The research also indicated a potential additional 13-15 percent – improvement in savings.

Nomenclature

C	Mass fraction
H	Opening vertical height
I	Turbulence intensity $I = \sqrt{2k/3V_{mean}^2}$
k	Turbulence kinetic energy
L	Display case length
$\dot{m}$	Mass flow rate
Re	Reynolds number, $\mathrm{Re} = \rho V w/\mu$
T	Temperature
V	Mean velocity at the DAG
W	Width
ρ	Density
μ	Viscosity
α	Offset angle (Figure 1)
β	Throw angle (Figure 1)

Introduction

Open refrigerated display cases are extensively used in supermarkets and grocery stores. Cold air is provided to the case interior through an air curtain emanating from a Discharge Air Grille (DAG) located at the top front of the case, and frequently, through holes in the back panel of the case. The air is re-circulated through a Return Air Grille (RAG), located at the bottom front of the case, to the evaporator heat exchanger.

The top-down flow of cold air creating an invisible barrier between the refrigerated space and the warmer outside air is called the air curtain. However, the mixing between the cold air curtain and warm store air cannot be avoided resulting in part of the cold air spilling over the display case and being replaced by warmer outside air. The amount of warm air that moves into the display case through the RAG is called the infiltration rate, and is responsible for most of the cooling load and thereby the power consumption. Since approximately 80 percent of the refrigeration load is caused by warm air infiltration, the air curtain performance becomes an issue.

The air curtain flow is a fluid mechanics problem involving a free jet creating turbulence mixing. The computational fluid dynamics simulation and validation of air curtain with flow visualization and turbulence intensity measurement techniques utilizing PIV, was previously reported in the past [1-2]. There have also been studies regarding the impact of geometrical configurations on the effectiveness of the air curtain performance [3-5]. These studies indicated that the turbulence intensity, the shape of the velocity profile at the DAG and the geometrical design of the canopy before the DAG, can alter the infiltration rate significantly. A comprehensive discussion of all the previous works in this area is reported in Reference [3].

During the research, it became clear that the infiltration of warm air into an Open Refrigerated Display Case (ORDC) was a function of both flow, and geometrical parameters. However, there was no accurate method of measuring the total flow rate in an ORDC except for the ad-hoc measurements of the velocity at inlets or outlets of the flow. It is known that these units go through the cycle of frosting and defrosting periods and the air flow rate changes during this operation. Therefore, a method with a reasonable level of precision that is able to measure the total air flow rate inside an ORDC in real time, during the normal operation, was yet to be developed. Furthermore, PIV, or CFD tools, can be used to solve a specific problem, but they cannot be used as an engineering tool with a fast turn-around time for the optimization of the air curtain performance due to their complexities and time requirements in their usage.

The tracer gas technique was developed to monitor the total flow and infiltration rates in an ORDC. Furthermore, to develop an engineering tool, certain parameters that can affect the infiltration rate were identified from all previous works. Then a matrix of all flow and geometrical parameters, which spans between a minimum and maximum, with a few intermediate values in between, was constructed. A modular ORDC was constructed in which all parameters could be altered, and the infiltration rate was measured over the entire test case matrix. Because of the matrix, now any other scenario can be predicted (or interpolated) from this set of data. However, this is a multi-dimensional problem and a more intelligent process to predict the infiltration rate, based on provided flow and geometric data, could be developed by using an Artificial Neural Network (ANN) program. This ANN could be used to immediately predict the infiltration rate based on the provided input to perform parametric studies. That is to say, those flow variables, or geometric specifications, that can lead to lowering the infiltration rate could be easily identified. The development of this engineering tool is the focus of this paper.

Formulation

The schematic of an ORDC and its geometric parameters are shown in Figure 1.

The offset angle α is defined to specify the location of RAG with respect to DAG, and the throw angle is β. Every length is normalized with respect to the DAG width, W_{DAG}. The Reynolds number is based on the DAG width and velocity. The modular display case in which these geometric parameters, including the fan speed and the percentage of the total flow rate being discharged from the back panel that can be altered, are shown in Figure 2. Furthermore, the design ensures almost laminar flow at the DAG (maximum 2 percent turbulence intensity was measured by PIV). The laminar flow at the DAG will produce the minimum infiltration rate. However, to determine the effects of turbulence intensity at the DAG on the infiltration, researchers induced turbulence at the DAG by inserting flappers and measuring the infiltration rate.

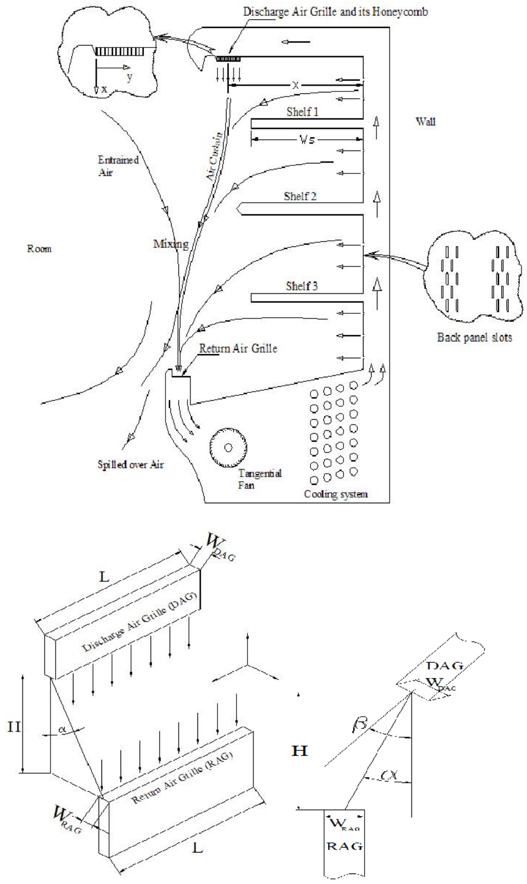

Figure 1. Schematic of an ORDC and the definition of geometric specifications

Generally, the turbulence intensity at the DAG in an actual ORDC, could be as high as 20 percent. A ½ scale open display case was built for testing. The following relationship relates the normalized infiltration rate to the flow and geometric parameters. Note that the effects of turbulence, relative humidity (RH), and temperature are treated as a correction factor to the function.

$$\frac{\dot{m}_{inf}}{\dot{m}_{tot}} = f\left(\frac{H}{w_{DAG}}, \alpha, \beta, Re, \frac{\dot{m}_{BP}}{\dot{m}_{tot}}\right) \times g\left(\frac{T_{DAG}}{T_{Rm}}\right) \times \Omega(RH) \times \Phi(I) \quad (1)$$

However, numerous experimental results indicated that the turbulence intensity, temperature, and relative humidity will have almost the same affect for different values in the first bracket (function *f*). Therefore, to reduce the number of required experiments, the decision was made to treat these terms as a correction function. It should be noted that turbulence intensity significantly affects infiltration. However, this effect is not significant as the parameters inside the first bracket change.

It has also been shown in Reference [6] that the following equation can be used to find the normalized infiltration rate in Equation (1).

$$\left[\frac{\left(C_{CO_2}\right)_{DAG}-\left(C_{CO_2}\right)_{RAG}}{\left(C_{CO_2}\right)_{DAG}-\left(C_{CO_2}\right)_{Room}}\right]=f\left(\frac{H}{W_{DAG}},\frac{\dot{m}_{BP}}{\dot{m}_{Total}},\mathrm{Re},\alpha,\beta\right) \quad (2)$$

Experimental Setup

A modular display case, shown in Figure [2], was constructed.

Figure [2]The modular display case

The infiltration rate, within an open refrigerated display case, can be directly measured by using carbon dioxide as a tracer gas. Carbon dioxide was used as the tracer gas, and a gas analyzer was used to monitor the CO_2 concentrations at the DAG, RAG, and in the room as indicated in Equation (2). The details of the setup are demonstrated in Reference [6]. Sampling probes 1, 2 and 3 measure $(C_{CO2})_{DAG}$, $(C_{CO2})_{RAG}$, and $(C_{CO2})_{Room}$, respectively, which are used to calculate the non-dimensional infiltration rate shown in Equation (2). In this display case, it is possible to change all the problem variables (on the right side of equation 2), enabling researchers to measure the infiltration rate for all permutations. A maximum and minimum "recommended possible" value for each parameter was set, and levels between the maximum and minimum of each variable specifying the total number of permutations or experiments to be performed were determined. In Table 1, the assumed maximum and minimum values, and the number of levels for each variable are presented. It can be seen that as the number of variables increases, the required number of experiments also increases significantly. Furthermore, as the number of levels increases, the number of infiltration rate measurements also grows considerably. The number of levels, and the minimum/ maximum for each variable, was considered after numerous consultations with a team of experts and researchers from universities, organizations, and manufacturers. To cover the entire range of operation, it was determined that a total number of *576* experiments should be performed. It was theorized that if the number of parameters and levels which define the matrix resolution were increased simultaneously, the total number of required data points (numerical or experimental) would become prohibitively large.

Table 1 Maximum and minimum and number of levels for each variable

Variable	Min.	Max.	Values	Levels
H/W_{DAG}	8	16	8,12,16	3
$\dot{m}_{BP}/\dot{m}_{Total}$	0	1.0	-	4
Re	2000	8400	2000, 3400, 5500, 8400	4
α	0°	24°	0°, 16°, 24°,	3
β	-7°	13°	-7°, 0°, 5°, 13°	4

The modular display case was used to sweep over the entire test case matrix displayed in Table 1, and is referred to as the input matrix hereinafter. There were an additional 42 experiments conducted to identify an expression for the functions that include RH, temperature, and turbulence intensity in Equation (1). The acquired data was used to train an ANN program that was used to perform parametric studies and identify only one alternative design that could lower the infiltration rate. The end-cost of manufacturing and fabricating a new display case design was a consideration in making changes to a base case to prove the validity of the research team's approach. Every effort was made to identify a simple, low-cost design change.

Validation

The validation process involved measuring the infiltration rate in an open refrigerated display case. This measurement is referred to as the "Base Case." In the next step, the ANN was used to examine the impact of the parameters indicated in Table 1 on the infiltration. These parameters were changed within values between the minimum and maximum. Several options became available. Researchers chose the option that indicated a reduction in average velocity at the DAG from approximately *27* to *19 m/min* and a throw angle of -7°. This was primarily due to the simplicity of making this change as compared to any other geometrical alteration except the throw angle. Table 2 shows the measured values for the Base Case.

Table 2 Specs of the Base case

β	*W* *(cm)*	*L* *(m)*	*H* *(m)*	*Offset length (cm)*	V_{DAG} *(m/min)*	$\dot{m}_{Total}$ *(m³/min)*
0	7.85	2.	1.37	15	27	11.5

The infiltration rate for the Base Case was calculated and measured using the ANN program. The turbulence intensity at the DAG for the Base Case was measured at approximately 12.5 percent by using PIV. Researchers also examined the infiltration rate with and without the food products. These results are indicated in Table 3, Where it can also be seen that the increase in turbulence intensity from 2.5 percent to 12.5 percent at the DAG increased the infiltration rate significantly. The comparison of normalized in filtration also showed that the ANN predicted-value and measured-value coincide. This result was an unanticipated coincidence.

Table 3 Comparison of Normalized Infiltration

Normalized Infiltration (% of Total Flow)					
Without Food			With Food (50% filled)		
ANN 2.5%	ANN 12.5%	Measured	ANN 2.5%	ANN 12.5%	Measured

22	28.8	27.1	26.5	35.3	35.3

A prototype case with a lowered DAG average velocity was built and tested. The specs of the prototype case are given in Table 4.

Table 4 Specs of the prototype case

β	*W* (*cm*)	*L* (*m*)	*H* (*m*)	*Offset length* (*cm*)	V_{DAG} (*m/min*)	$\dot{m}_{Total}$ (m^3/*min*)
-7	7.85	2.	1.37	15	19	12.5

Table 5 shows the infiltration rate for the prototype case when 50 percent of the case was filled with food products. This produced an interesting result because the total flow rate and turbulence intensity at the DAG in the prototype was higher than the Base Case, yet the infiltration rate was still lower. It was also noted that the ANN prediction was very accurate and is concurrent with the measurements.

Table 5 Predicted and Measured Infiltration for the Prototype case

Normalized Infiltration		
With 50% food Products		
ANN TI=2.5%	ANN TI=14.5%	Measured
21	30.8	28.3

Although this reduction was approximately 7 percent, the reduction could potentially be greater if the flow rate and turbulence intensity were closer to the Base Case. Due to this 7 percent reduction in the infiltration rate, it was expected that the cooling load also be reduced. Therefore, the compressor suction pressure was reduced and an energy savings of about 12 percent was observed over a one day period of operation. The reduction in infiltration and compressor suction had no impact on the food product temperature. This indicated that the unit is still generating enough momentum at the DAG without compromising the integrity of the air curtain. The detailed testing results and temperature distribution inside the case can be found in Reference [7].

Conclusions

The neural network algorithms were successfully implemented to predict the infiltration rate of an actual display case based on experimental data obtained with a ½ scale modular display case. The ANN was used to find one of the possible specifications that led to the design of an optimum display case. A prototype display case was manufactured based on the ANN recommendations and the actual test results indicated a 12 percent reduction in the power consumption which is quite encouraging. Another area of improvement, the reduction in the turbulence intensity at the DAG, was also identified.

Acknowledgements

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