Calculation of Heat Flow across Doorways in a Food Supermarket

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ABSTRACT

The main objective for installing doors in buildings is to provide easy access to the building as well as conserving the indoor thermal environment. Large supermarket chains attract high footfall and doors are designed to cope with a large influx of people. Access and egress in supermarkets are achieved through the same doors, hence keeping doors open for a substantial amount of time and creating the perfect environment for uncontrolled ventilation. Supermarkets install wind lobbies at the front of main entrance/exit doors to reduce uncontrolled ventilation; however, little research has been done regarding the operational effectiveness of wind lobbies.

To understand the pattern of heat flow across doorways within a typical wind lobby, a Computational Fluid Dynamic (CFD) model was constructed to examine the interaction between indoor and outdoor environment. The dimensions of the wind lobby and doorways in the CFD model were based on an actual and fully operational store and include an air curtain. Preliminary results from the CFD simulation suggest that the air curtain is not as effective in limiting uncontrolled ventilation when external wind speed is 5 m.s⁻¹ and temperature is 0 °C when compared to external wind speed of 1 m.s⁻¹ and 5 °C. Further analyses to include quantitative evaluation of heat loss for different wind lobby and air curtain configurations.

Keywords:
Wind lobby, Doorways, Heat transfer, Uncontrolled ventilation, CFD

1. INTRODUCTION

Natural ventilation strategies and how to estimate airflow through openings are well documented in the literature. Empirical equations to calculate the rate of air-flow through openings are available Awbi (2003, pp. 110) and BS (1991). These equations are generic and do not take into account the location of an opening. Costa et. al. (2011) carried out an investigation into the impact of the location of an opening on the amount of airflow through it and found that it’s location on the facade can affect the amount of air flow through the opening. A Building’s orientation to the wind direction also influences the airflow and pressure distribution around it which affects the air infiltration through openings (Kasperski, 2007). Internal layout can also affect wind velocity and comfort inside the store (Kindangen, 1997).

The earliest study found in literature to estimate natural convection through doors was carried out by Brown and Solvason (1962), the study focused on natural convection through a single door in uncontrolled weather condition. Similar studies were carried out by Said et. al. (1993), Hendrix et. al. (1989), Yuill et. al. (1968) and Kiel and Wilson (1968), all these studies focused on pure natural convection due to temperature difference between two zones. Barakat (1987) carried out a review of inter-zonal heat transfer in buildings and found that attention was mainly paid to natural convection studies and did not taking into account combined forced and natural convection.

Entrances in supermarkets are the primary cause of uncontrolled ventilation in the stores. Large food stores have larger openings to provide easy access and egress to customers with trolleys and baskets. Door size is specified in accordance to the store size; some supermarket chains have their own
regulations that they have to meet and these regulations should match the building regulations. The uncontrolled outdoor air penetration to the store creates an imbalance between supply air and the extract and could cause discomfort for people due to pressure change inside the building (Tassou et al., 2011). To limit uncontrolled ventilation, supermarkets usually install so-called “wind lobbies” at the main entrances which have to conform to the relevant building regulation and standards. In a similar layout to a wind lobby, Allarad (1998, pp. 70-71) suggests that an average of 36% to 51% of air acting on the external doors will flow into the store. Calculations of heat flow through doorways in a layout similar to modern supermarkets are rare.

[An approach to estimate heat removed from a space by considering convective heat flow is provided by Artman et al., (2010)]. The aim of this paper is to calculate heat flow across the doorways in the presence of an air curtain and wind lobby. The calculation of heat flow is based on temperature and velocity data obtained from a Computational Fluid Dynamic (CFD) model and the CFD model was evaluated against real temperature data which was collected on site of a typical supermarket.

2. METHODOLOGY

Lack of in-situ data and flow modelling within food supermarkets has made it difficult to estimate the effect of uncontrolled ventilation through main doors. To determine the cause of uncontrolled ventilation, it was decided that the best method to adopt for this investigation was to carry out detailed measurements of temperature by placing temperature measurements inside the store, lobby and outside the store at different heights (Wang et al, 2009 and Oreszczyn et al., 2006) and to use the collected data to evaluate a CFD model. For the study, a supermarket of typical design with a wind lobby attached to it was chosen.

2.1. Site Description

The Tesco store in Brighouse in West Yorkshire, (latitude and longitude are 53.70387 and -1.78365 respectively) was selected for the monitoring program. The store is located in a sub-urban area, with no adjacent buildings attached to it. The supermarket has an approximate sales area of 5000 m² and the wind lobby is outside the store and located on the west side and has a gross internal floor area of 53 m². Figure 1(a) shows the store surroundings and figure 1(b) the aspect of the wind lobby which has dimensions 10 × 5.3 × 4m (length × width × height).

Figure 1  a) an aerial view of the store and surroundings, the rectangle with dashed red line indicate the approximate location of the wind lobby b) Plan view of the lobby layout, dark dots with numbers inside represent the approximate position of the monitoring sensors; arrows indicate the flow of people in and out of the store. The rectangle with dashed line represents the air curtain.

Access from outside the store to inside the wind lobby is provided through automatic opening sliding doors, with dimensions 2.4 × 2.2 m (width × height), that are installed on the north and south sides.
Two automatic opening doors leading into the store are installed on the east side of the lobby with dimensions $2.8 \times 2.2\,\text{m}$ (width $\times$ height) for Door 1 and $2.2 \times 2.2\,\text{m}$ (width $\times$ height) for Door 2.

The walls including doors are mainly constructed of single glazing glass and the roof is constructed of metal cladding. There is an air curtain installed 1.3 m away from the main store doors at 2.3 m height. The purpose of the air curtain is to provide aerodynamic sealing to the store by pressurizing the entrances to limit uncontrolled ventilation penetrating to the store. The western side of the store’s façade is constructed of glass.

2.2. Instrumentation

Tinytag data loggers were installed in the store to collect data. Two models of the data loggers were installed and these are (TGU-4500) and (TGP-4500) for internal and external use respectively. Data loggers were calibrated prior to installation in the store to ensure that accurate readings are recorded and processed.

The calibration process was carried out by placing the data loggers inside an environmental chamber, and the data obtained from the chamber were compared to the data from the Tinytag sensors over the same period of time. The range of test temperatures that was experienced in the chamber was from -10 °C to 40 °C. The temperature in the chamber was set to rise in steps; each step represented a 10 °C rise in the chamber temperature. A total number of 6 steps were considered: a transitional period from one step to another was assigned to be 10 minutes and each step was undertaken for 45 minutes to ensure that the sensors were fully adjusted to the new temperature and the A different range of temperature bias was experienced in the sensors, the minimum bias was found to be 0.68 °C, maximum was 1.4 °C and the average was 1.2 °C. Measured temperatures were corrected for these biases before comparison.

2.3. Experimental Set-Up

To ensure capture of vertical and horizontal temperature distribution, 17 Tinytag (TGU-4500) data loggers were installed at different locations inside the wind lobby and the store to measure temperature every 2 minutes. A single Tinytag (TGP-4500) was installed outside the store to measure the outdoor temperature. A preliminary Computational Fluid Dynamics (CFD) simulation was carried out to estimate the best location for the sensors based on the airflow inside the lobby. Ideal locations were identified as being areas away from vortices created by opening and closing of the doors. However, the identified locations from the CFD simulations could not be used due to practical reasons, e.g. sensors had to be mounted on walls. Therefore, sensors were installed in secure places and where solar gain was minimal.

Sensors inside the lobby in position 2 were installed on the west wall, which constructed of $2.5 \times 0.9\,\text{m}$ (width $\times$ height) pieces of glass joined together by vertical frames. Frames were located at fractions of 0.25, 0.50 and 0.75 of the total length of the lobby which is 10 m and sensors were placed on the frame at 1.1 and 2.2 m height. The lower sensors at doors 1 and 2 and inside the store were installed at 1 m rather than 1.1 m due to practical restrictions. Due to practicality issues door sensors were installed 0.6 m inside the store and 0.70 m away from the air curtain. The fan of the air curtain is switched on continuously to provide aerodynamic sealing at doors 1 and 2. When the outside temperature is under 10 °C, the air curtain will provide heated air at 19 °C. Sensors inside the store are installed 0.1 m away from the external wall, again due to practical limitations, sensor were placed 9 m from Door 2 at 1 and 2.2 m height. Table 1 below provides the heights of the sensors with reference to the location of sensors on Figure 1(b). Temperature measurements were collected from February 2012 to February 2013.
### Table 1 Heights of upper and lower sensors at each measurement location

<table>
<thead>
<tr>
<th>Sensor Position Reference (Fig 1(b))</th>
<th>Location</th>
<th>Lower Sensor Height (m)</th>
<th>Upper Sensor Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Outside store</td>
<td>-</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>Middle of Lobby</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>3</td>
<td>Door 1</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>Door 2</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>5</td>
<td>Inside Store</td>
<td>1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

### 3. COMPUTATIONAL FLUID DYNAMICS (CFD) MODEL

CFD was chosen for use in this project because of its ability to examine different scenarios. Firstly, a realistic representation of the store is established and verified with experimental temperature data. The software will then be used to generate results from many different scenarios in a short space of time, and these scenarios will be examined for their suitability to supermarkets. For this research the software package CFX by ANSYS was used. In this paper, the evaluation of the temperature simulation and preliminary results for heat flow across the doorways is presented.

#### 3.1. Geometry and Meshing Generation

ANSYS design modeller software was used to produce the model. The size of the lobby in the model is based on actual lobby dimensions for width, length and height. The west side of the store was based on actual length; width of the store in the model is not based on the actual store, the width was reduced to 20 m to reduce the domain size and hence computational time. The height of the store in the model is equal to the actual height. The environment domain was represented by a larger box; the dimensions of the environment are shown in Figure 2(a) for width, length and height respectively. Dimensions of the wind lobby for length, width and height, and main doors are based on actual sizes.

When numerically solving the system of equations, mesh quality and type have an impact on the simulation results Hefny and Ooka (2009). Different types of mesh are available, but for the purpose of this mesh, hexahedral mesh was generated using ANSYS ICEM-Hexa meshing tool. Guidance on generating a good quality mesh to simulate airflow in buildings is provided in REHVA Guide book 10 and these were followed to test the quality of the mesh. This mesh is preliminary and sensitivity analyses will be carried out to test the grid. The boundary layer thickness was calculated to be 6 cm with growth rate of 1.2. The total mesh size was restricted to 25 million cells due to the available computer power. Figure 2(b) shows the model after meshing.

Figure 2 a) A schematic view of the model including store, lobby and the environment; b) view of the store and lobby after meshing. For a better view of the model, only the ground surface was shown in the domain.
3.2. Model set-up

The model was divided into three domains which are Environment, Lobby and Store. The domains were connected together; flow is computed in the outer domain, and then used as boundary condition for the next domain. Four cases in total were set up under four outdoor conditions and these were 0 °C, 5 °C and 1 m.s⁻¹ and 5 m.s⁻¹. Wind direction for all four simulations cases assumed wind flying from north to south and the air curtain was set up to provide constant air at 4.5 m.s⁻¹ and temperature was 19 °C, store indoor temperature was set up to be 19 °C. SST turbulence model was used for all simulation cases under steady state condition.

3.3. Model evaluation

CFD models should be validated against real data to check whether the model is behaving in a similar way to real life. The model was validated by comparing indoor and outdoor temperature measurements to those obtained from the CFD model. Temperature values as measured for 10 minutes were averaged and selected which is equal to the CFD value 5 °C and wind speed of 1 m.s⁻¹ and the temperature was compared at three places: middle of the lobby and by door 1 and door 2 (positions 2, 3 and 4 on figure 1(b)). The sensors readings were taken at two heights and temperature data from the CFD model were extracted at a similar height to the sensors. Data presented here are based on the two outdoor temperature conditions which are 0 °C and 5 °C. These conditions are of interest as under these conditions CFD simulations were carried out.

The temperature comparison in figure 3 was obtained from averaging 5069 in site samples; these 5069 values were selected when the outdoor temperature was between 4.5 °C and 5.5 °C between 1st Oct 2012 to 1st Feb 2013. No considerations were given to time of day and to whether the store was open or closed and air velocity on site was not known. Mid lobby temperature from in situ data and simulation show agreement and the in situ temperature does not vary this could be attributed to the fact that there is no active heat source in the lobby to influence temperature in the middle of the lobby. There was a considerable difference in temperature between simulated and in situ temperature at doors 1 and 2. This could be attributed to the presences of an air curtain and it was having an influence on the flow at doorways. Another possibility is that the simulated temperature was obtained from steady state simulation assuming that the lobby doors and doors 1 and 2 were open, in reality, these are sliding doors and they open and close when there are customers going in and out of the store. At door 2, it appears that the simulated and real temperature follow a similar pattern, however the gradients are strong. At door 1 both the pattern and gradient are different.

![Figure 3 Comparison between actual on site temperature and CFD temperature at a time.](image)

Further evaluations of the CFD model are currently being undertaken to validate the model and to an understanding of the flow at doorways. Despite the present shortcomings in the model, the simulations are analysed to give heat flow across the doorways.
4. HEAT FLOW AT THE DOORWAYS

Heat flow is driven by temperature difference, in the presence of dominant wind speed, heat flow can be affected by the direction of the wind. Therefore, the most important parameters for calculating heat flow are temperature difference and the direction of the wind. The size of an opening is another important factor when calculating the total heat flow. A method to calculate convective heat flow is followed to estimate the heat loss. The total heat loss was calculated based on paper written by Artmann et. al. (2009), the paper provides a methodology to calculate heat removed from a space as provided in equation 1 below:

\[ Q = u_{\text{air}} \rho C_p (T_{\text{in}} - T_{\text{out}}) \] (1)

In the case of this paper, \( T_{\text{in}} \) is always higher than \( T_{\text{out}} \) and this leaves \( u_{\text{air}} \) as the dominant force, positive sign indicate the air is penetrating the store and negative sign indicate air leaving the store.

4.1. Air velocity at doorways

Only one component of the wind velocity was of interest Figure 4 provides details of the \( u \) component of the wind vector perpendicular to doorways; these values were obtained from the CFD model.

![Figure 4 u-component of wind vector perpendicular to doorway](image)

4.2. Average Temperature at doors

Temperature data at the doorways extracted from the CFD model indicate that high outdoor air velocity has an impact on the temperature distribution at the doorways. The CFD model was simulated under two temperature 0 °C in and 5 °C conditions and for each temperature case, the outdoor wind speed was fixed at 1 m.s\(^{-1}\) and 5 m.s\(^{-1}\). air curtain was assumed to be ON and supplying air at 4.5 m.s\(^{-1}\) at 19 °C, therefore the total number of test cases was four.

![Figure 5 a) comparison between temperature at doors 1 and 2 and 10 cm inside the store under outdoor temperature of 0 °C and air velocity of 1 m/s and 5 m/s; b) comparison between temperature at doors 1 and 2 and 10 cm inside the store under outdoor temperature of 5 °C and air velocity of 1 m.s\(^{-1}\) and 5 m.s\(^{-1}\).](image)
4.1.4.3. Heat flow across the doorways

The amount of heat flow across doorways is provided in figure 5. Heat flow direction is dictated by the direction of the perpendicular air velocity acting on doors, therefore “positive indicates cold air flowing into the store”. It appears that the largest amount of heat loss occurred at door 1 when the outdoor velocity was 5 m.s\(^{-1}\) and temperature was 0 °C: this is due to the large penetration of cold air into the store driven by the wind. However, under the same outdoor conditions, door 2 had the lowest heat flow and this was mainly due to the low temperature gradient across the door. Negative heat flow in figure 5 at door 2 was a result of flow coming out of the store into the wind lobby, the only case in which this occurred. When outdoor air velocity is 1 m.s\(^{-1}\), it seems that the air curtain is having an impact on the environment on the flow at door 2.

![Figure 6 direction of heat flow](image)

5. CONCLUSION

To conclude, the issue of natural convection through doorways has been in research for decades. The main focus on research found in literature is on pure natural ventilation analogy; combined natural and forced convection are limited. This paper has focused on data collection from a typical supermarket store and the data were utilised to preliminarily evaluate the performance of a CFD model. Comparison of real data and CFD model data show that there is an agreement between both data sets in the middle of the lobby, at doorways, there is a difference between simulated temperature and in situ temperature. The difference could be attributed to the presence of the air curtain which influencing the flow at doorways, another possibility is that doors close and open when customers enter and leave the store and opening and closing of doors was not included in the CFD model.

The calculation that followed showed that door 1 has the highest heat flow when the outdoor temperature was 0 °C and air velocity was 5 m.s\(^{-1}\), this could be attributed to the size of door 1, large temperature gradient and high outdoor air velocity. Further model evaluation is needed before it becomes a credible design tool, and this would be achieved by testing the CFD model under various numerical and wind direction scenarios.

Nomenclature

\begin{align*}
  s &= \text{time in seconds}, \\
  Q &= \text{heat flow (watt)}, \\
  u_{\text{air}} &= \text{Volumetric Air velocity (m}^3/\text{s}), \\
  \rho &= \text{air density (kg/m}^3), \\
  C_p &= \text{specific heat capacity (J/kg.K)},
\end{align*}
\(T_{in} = \) temperature inside the store  
\(T_{out} = \) temperature at the door way

REFERENCES


