PE4.106 3D Distribution of F-values during Thermal Meat Processing 387.00

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Abstract—the degree of non-uniformity in 3D distribution of temperatures in a process room and among products were measured and visualised in order to determine the effect on the non-uniformity in the distribution of F-values at the end of a thermal meat process. Measurements were done in lab-scale (L x W x H: 0.9 m x 0.72 m x 1.5 m) and factory-scales (mean L x W x H: 2.3 m x 3.0 m x 2.0 m) to find out the consequent effects of room volume on the 3D spatial distribution of temperatures and F-values. In both scales, large differences in room temperatures (7ºC to 11ºC) and locations of the hot and cold zones (top and bottom, respectively) were found to be similar. All temperature measurements were found to be significantly different ($p < 0.05$). Thus, imperfect (non-homogeneous) mixing of heated medium actually occurred during cooking regardless of the volume of room due to several reasons, e.g. poor air circulation, low air injection velocity, and irregular air flow pattern, among others. Differences in product core temperatures in lab-scale were comparatively smaller than those in factory-scale. Subsequently, the non-uniformity of F-values was smaller in lab-scale compared to factory-scale measurements due to difference in process room volume/ density and product type. But in general, it can be concluded that non-uniformities in 3D temperature distribution inside process rooms and among product cores also lead to non-uniformities in the distribution of computed F-values.

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Index Terms—3D non-uniformity, F-value, temperature distribution, thermal meat processing.

I. INTRODUCTION

In cooking processes, important process variables such as temperature and relative humidity are rarely uniformly distributed inside a given volume of space. Studies made in laboratory installations [1]-[2], agricultural buildings [3] and food storage systems [4]-[5] showed significant spatial temperature differences due to imperfect mixing. Processes such as heating, cooling, and recirculation of air inside chambers can similarly lead to imperfect mixing of fluids and non-uniform micro-climate conditions. Besides non-uniformity in product quality (due to underprocessing, overprocessing, etc.), temperature non-uniformity can typically result to crucial problems on food safety (due to underprocessing). It is therefore important to establish a system of defining and quantifying the degree of 3D non-uniformity in temperature distribution inside food process systems and then use this insight to set optimal process conditions best suited to produce equally safe and high quality food products. Experimental monitoring of 3D temperature distribution will allow us to construct models for prediction and control of 3D process environment in meat processing systems. This research focused on identifying and quantifying the degree of 3D non-uniformity in temperature distribution inside the process chamber and among the products during thermal meat processing. Measurements were done in two different scales, namely, in laboratory-scale and in real-scale to compare the effect of process chamber volume in 3D spatial distribution of temperature and uniformity in product safety.

II. MATERIALS AND METHODS

LABORATORY-SCALE MEASUREMENTS

A. Laboratory-scale installation A laboratory-scale meat process chamber (Kerres JET-SMOKE-Universal Kammer Typ 1250 EL_RET, Germany) with inner airspace dimensions of 0.9 m x 0.72 m x 1.5 m (L x W x H) was used in the cooking experiments. The chamber has its own sensors (control sensors) for both room temperature and product core temperature. In order to measure and visualise the 3D distribution of airspace temperature inside the chamber during the process, 36 calibrated type-T wired thermocouples (Comark Ltd, UK) (diameter: 0.6 mm; mean accuracy: ±0.1°C) were positioned in a 3D-grid (2x3x6) positioned in a product cart. These sensors were referred to as grid sensors in the study. Two more thermocouples were placed at the end of the air inlets to record the temperature of the heating medium before being circulated inside the chamber.

Among the 14 experimental meat products (mean initial weight = 2.4 kg; mean length = 0.25 m; mean diameter = 0.14 m) hanging in three layers in the product cart, eight were chosen as points for measuring product core temperature by calibrated NTC-type probe sensors (diameter: 3 mm; probe length: 10 cm; mean accuracy: ±0.4°C). These product core temperature sensors were referred to as prikkers in this study. Both grid sensors and prikkers have a measuring range of -200°C to +400°C and a reaction time constant less than 3 s. For continuous collection of data, a multi-data acquisition system (Keithley 2700 Multimeter/ Data Acquisition System, USA) with a sampling frequency of 50 samples/s and an accuracy of ±0.2ºC was used. Figure 1 illustrates the lay-out of the grid sensors and experimental meat products in the cart.

B. The experimental set-up Two experimental batches were carried out. The first experiment involved a typical thermal meat process, i.e. heating followed by immediate cooling. The second experiment was carried out mainly to verify the consistency of 3D distribution of both room temperatures and product core temperatures during heating only. During the two cooking experiments, the control core sensor was placed inside products 5 and 13, respectively. The existing control system of the chamber terminates the heating process when the target core temperature is recorded by the control core sensor.

REAL-SCALE MEASUREMENTS

A. Factory-scale installations

Measurements in real-scale cooking chambers were done in five companies manufacturing cooked ham. Factory-scale experiments required a larger number of sensors and involved longer durations of data-logging and extreme process conditions. In this case, wireless sensors with an operating range of -20 to +85oC and a sampling rate of 1 s up to 273 hours (Thermochron iButton DS1921L-F51, Maxim/ Dallas, USA) were used. Data were obtained by connecting these sensors to a host system (PC or laptop) via a software interface. Similar to the lab-scale sensor lay-out, 36 wireless sensors were placed in one product cart. For process rooms with more than one cart-capacity, additional sensors were placed in the rest of the carts but the whole room was treated as one large 3D grid divided into three planes for easier data management and visualisation. Another sensor was placed beside the control sensor of the chamber for comparison purposes. Moreover, two more sensors were placed at the steam inlets (left and right) in order to have an idea of the temperature of the heating medium before it circulates inside large-scale chambers. After each cooking process, the sensors were removed and data were read for analysis.

3D VISUALISATION AND DATA ANALYSIS

The 3D spatial distribution of temperature inside process chambers and among the products were visualised through an algorithm developed at the Division of M3-BIORES. This program was run in Matlab (version R2007a, MathWorks, Inc., USA) using the temperature data obtained from the sensors. Basic descriptive statistics and one-way ANOVA (α = 0.05) were also used for data analysis. Non-uniformity in product safety was analysed by thermal process calculations in terms of F-value (reference temperature: 70°C; z-value: 10).

III. RESULTS AND DISCUSSION

A. Non-uniformity of temperature distribution in the process room

3D visualisation of measured temperature distribution inside the lab-scale chamber showed that non-uniformity indeed existed. The maximum temperature difference between the highest and lowest temperatures in the chamber was found out to be 11.2 ºC, with temperature values ranging from 39.7ºC to 50.9ºC. This occurred during the onset of cooling (come-down stage). At this stage, the lowest temperature (i.e. coldest spot) was found at the top middle left side of the chamber while the highest temperature (i.e. hottest spot) was found at the bottom front left side near the door. This was due to the fact that cooling was done by spraying cooled water directed from the corners towards the middle of the chamber. Thus, this resulted to faster cooling at the top middle region and slower cooling at the bottom, especially at the corners. The results were comparable to the temperature distribution in real-scale process rooms. Hottest zones were similarly found at the top near the steam/air inlets and coldest zones were found at the bottom, most commonly at the corners. The 3D visualisation of measured temperature distribution in one of the real-scale process rooms is shown in Figure 2.

Average difference in measured temperatures inside the process rooms was as large as 7.0°C. In all of the companies, temperatures measured by the grid sensors at more than 36 points inside the room were found out to be significantly different ($p<0.05$) during heating. Measuring temperatures at a maximum of 36 positions in a product cart enabled a closer visualisation of the immediate environment of the products (Figure 3). Through this, the locations of the hottest and coldest zones around the products and the large temperature differences (mean of 6.0°C) during cooking were thus confirmed.

B. Non-uniformity of core temperature distribution among products

In the lab-scale experiments, the 3D spatial distribution of product core temperatures was visualised at the time the target room temperature was achieved during heating. Product cores located at the top of the cart appeared to be hotter compared to product cores at the bottom of the cart. Frequency analysis of the highest and lowest temperatures recorded by the prikkers throughout the heating process revealed that the measured core temperatures of product 5, located at the top right side, has always been the highest (100%) while those of products at the bottom, i.e. product 11 (69.5%) and product 13 (30.5%) has always been the lowest.

The maximum temperature difference during heating was 1.7 ºC. This difference was relatively large, considering a prikker accuracy of ±0.4ºC and an acceptable core temperature difference of ±0.5ºC. Moreover, measured product core temperatures were found to be significantly different from each other ($p<0.05$). In real-scale measurements, similar locations of the hottest and coldest product cores were observed. Figure 4 shows an example of 3D visualisation of product core temperature distribution in real-scale, where the temperature difference was as large as 3.5°C. Core temperatures measured by the prikkers were also found out to be significantly different ($p<0.05$) during heating in all of the companies. Since the safety of thermally-processed products depends on the adequacy of heating at the coldest point inside the product (in this case the product core), it is highly important that core temperature differences among products be very minimal at any given time during the process.

C. Non-uniformity in the 3D distribution of F-values

Final F-values were considered after a full thermal cooking process, i.e. heating followed by immediate cooling to respective target core temperatures. Product core temperature is known to have the most significant effect on F-value. A deviation of 1.7ºC in product core temperatures measured in a lab-scale process chamber resulted to a maximum difference of 2.1 min. This difference in final F-values can be considered relatively small but it has to be noted that F-values were based on measurements done in a limited number of products (i.e. eight) inside a small-scale process chamber. In real-scale measurements, large deviations in core temperatures apparently produced substantial variations in final F-values as seen in Figure 5.

In this case, a difference of 3.5°C in product core temperatures caused a large difference in F-values (14.5 min).This can be explained by the fact that F-values are cumulative throughout the thermal cooking process. Furthermore, the 3D distribution of F-values at the end of the cooking process showed that products at different positions that have achieved different final core temperatures (Figure 4) also achieved non-uniform F-values (Figure 5). Thus, products with the lowest F-value can be underprocessed and products with the highest F-value can be overprocessed.

IV. CONCLUSION

The actual existence of large differences in 3D distribution of temperatures inside different size-scales of chambers was proven in this study. These large differences (11.2°C in lab-scale and mean of 7.0°C in real-scale) generally occurred at the onset of or during transition stages, i.e. come-up and come-down. Aside from 3D visualisation, frequency analysis of the highest and lowest temperatures recorded by the grid sensors throughout the heating process can be done to confirm the locations of the coldest and hottest zones. Temperature distribution among product cores was also proven to be non-uniform through 3D visualisation. Similarly, the hottest and coldest product cores during heating in both scales were found to be at the top and at the bottom, respectively. This implies that imperfect (non-homogeneous) mixing of heated medium actually occurred during the cooking process regardless of the volume of the process room and can be attributed to several reasons such as poor circulation of air, lower velocity of injected heating medium, and irregular air flow pattern, among others. These non-uniformity problems consequently lead also to non-uniformity in the 3D distribution of computed F-values.

However, the effects of non-uniformities in temperature distribution in the room and among the products differ with the process room volume, product type, and the number of points measured. It is thus recommended that more measurements points in the room and in the products be done to better visualise the 3D non-uniformity in temperature distribution and verify the process room volume factor on the 3D non-uniformity of F-value distribution.

ACKNOWLEDGEMENT

The authors would like to thank IWT-TETRA for funding this research.

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Table 1. List of Symbols

Symbol	Definition
α	Statistical level of significance
L	Length, m
H	Height, m
p	Statistical level of probability
s	Seconds
W	Width, m

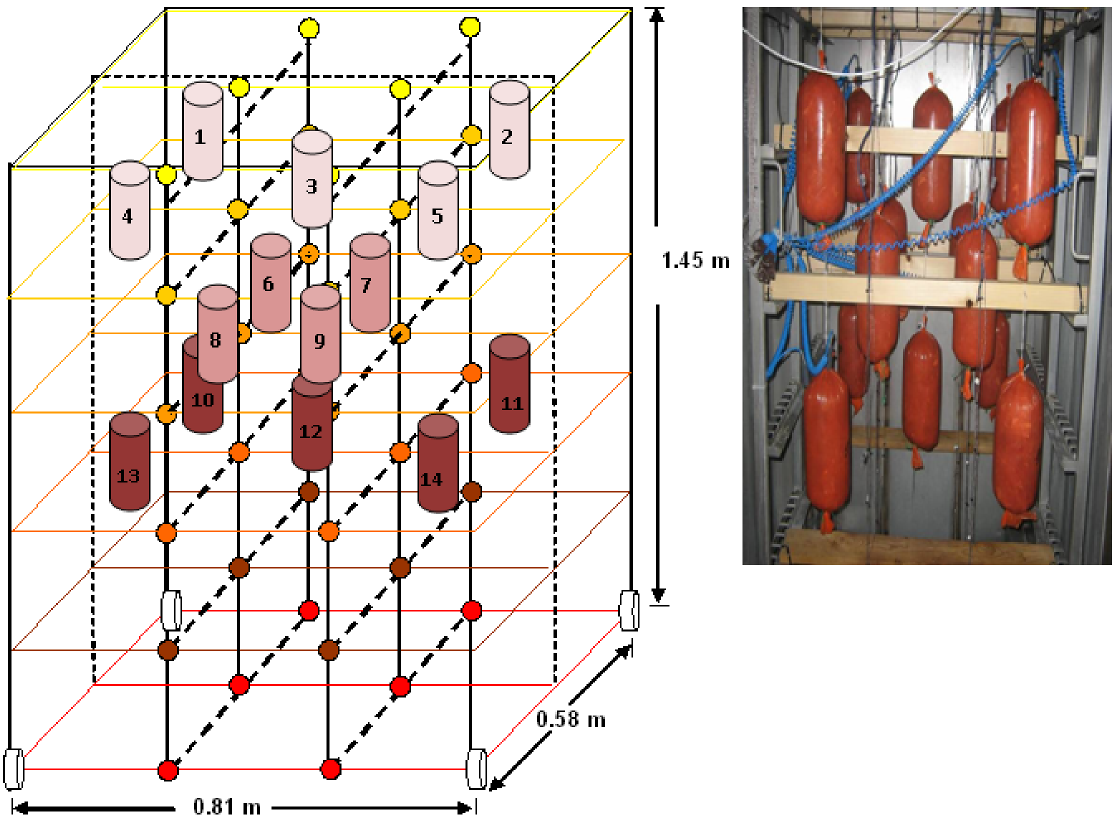
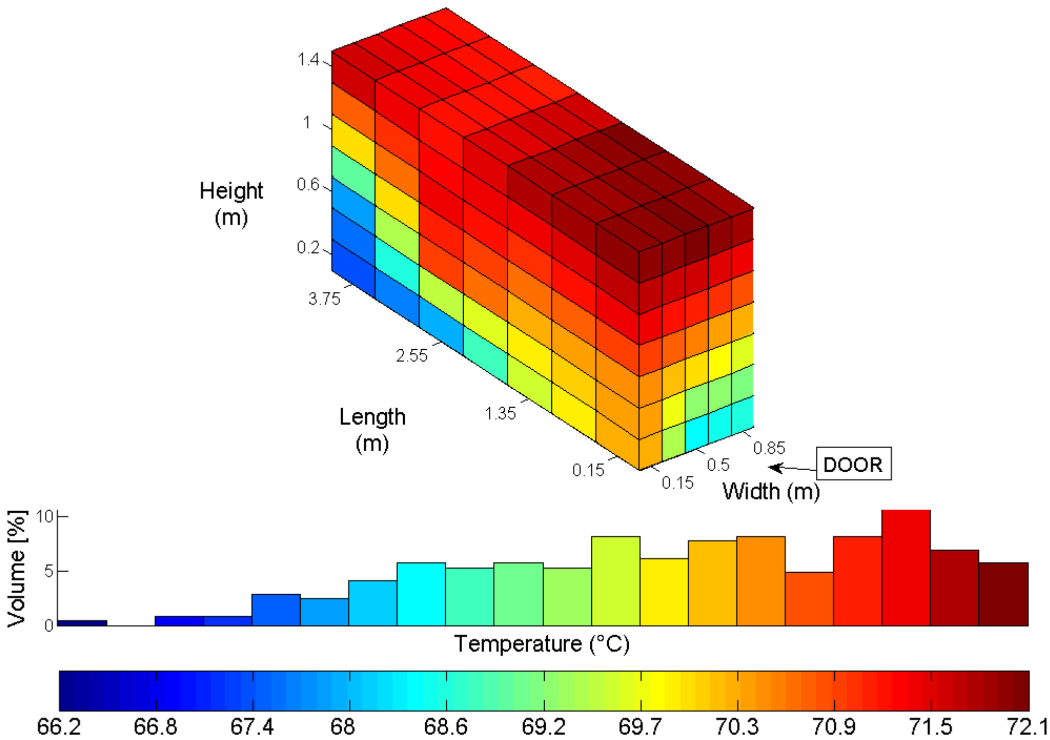

1.45 m
0.58 m
0.81 m
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Figure 1.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(m)
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1
0.6
0.2
3.75
2.55
1.35
0.15
Length
(m)
0.85
0.5
0.15
Width (m)
DOOR
Volume [%]
10
5
0
Temperature (°C)
66.2
66.8
67.4
68
68.6
69.2
69.7
70.3
70.9
71.5
72.1

Figure 2.

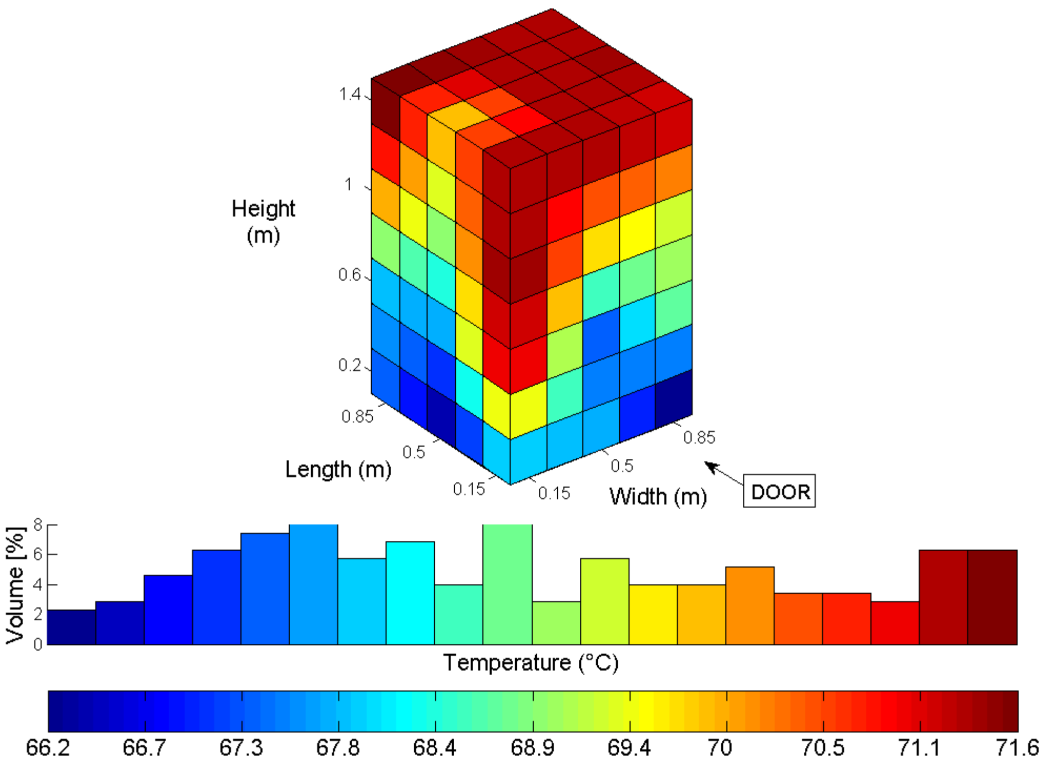

Figure 3.

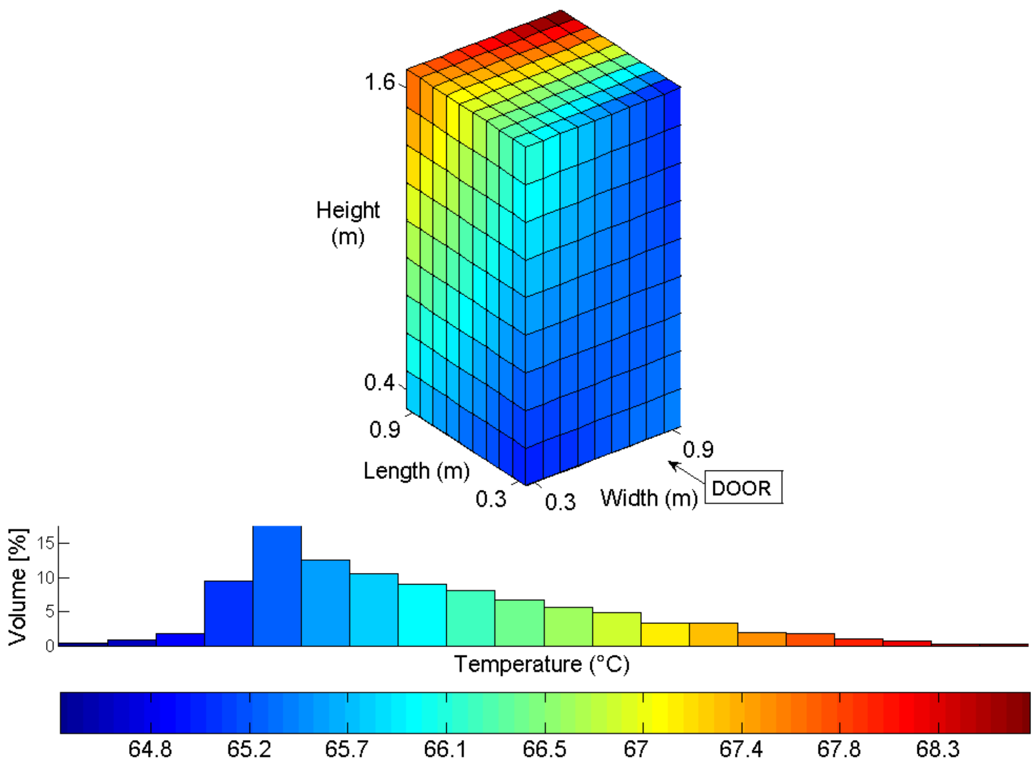

Figure 4.

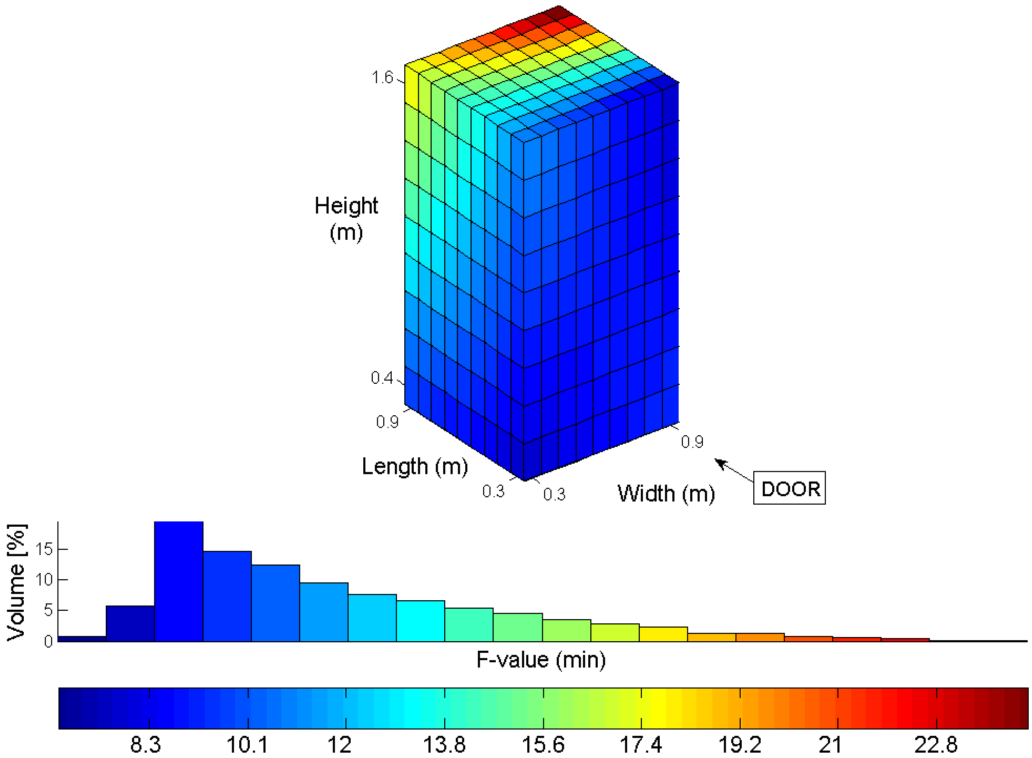
1.6
Height
(m)
0.4
0.9
Length (m)
0.3
0.3
Width (m)
0.9
DOOR
Volume [%]
15
10
5
0
F-value (min)
8.3
10.1
12
13.8
15.6
17.4
19.2
21
22.8

Figure 5.