Experimental verification of analytical and CFD predictions of infiltration through cold store entrances

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Abstract

Measurements of infiltration through different size entrances of a cold store at two different cold store temperatures were taken and compared against established analytical models and computational fluid dynamics (CFD) models. The analytical and CFD models generally tended to over predict the infiltration. The analytical model developed by Gosney et al provided the closest comparison with the various experiments. The CFD models were more accurate than the fundamental analytical models but less accurate than those based on a semi-empirical approach. For the experimental configurations examined, CFD offered no real advantage over these empirical analytical models. If the conditions were such that the infiltration rate changed with time or if door protection devices (e.g. air curtains) were used, CFD would become much more advantageous in predicting infiltration.

Key words: Cold store; Air flow; Computational fluid dynamics (CFD), Modelling, Measurements

1. Introduction

Infiltration of warm moist air through doorways into cold storage rooms during loading and unloading causes many problems to the operators. These include

- increased costs for running [1] and defrosting the refrigeration system
- safety problems associated with the mist formed in the doorway, as the cold air mixes with the ambient air [2].
- safety problems associated with ice forming around the door opening, on the floor and on the ceiling [2]
- food quality, safety and weight loss caused by temperature fluctuations.

The basic theory for natural convection of fluids at different densities through openings was expressed more than 70 years ago [3]. Since then many authors have come up with improved models [4], [5], [6], [7], [8], [9]. All of these analytical models are based on ideal flow theory, and the later models, contain a coefficient to account for viscous and thermal effects. Hendrix et al [10] has compared these models against real measurements and found that they generally over predict the volume flow rate through the door. Chen et al [1] found that the empirically based model due to Tamm [5], over predicted the air infiltration rate through an open door by 30%. Chen suggested that further measurements needed to be carried out on a wider range of cold stores, door sizes and operating conditions to confirm results and establish the generality of the empirical factors.

For small cold stores, during door opening, the temperature inside and outside the cold store will change with time and height. As the analytical models assume a constant temperature either side of the door, they are obviously limited. If an air curtain is operating, these models are inapplicable.

A computational fluid dynamics (CFD) model can predict the change in temperature with time and space both inside and outside the room and can model the effect of air curtains. CFD has been used to model cooling times in an air blast-chilling process [11], air-flow in a cold store [12], [13], [14], temperature rise during distribution [15], and heat and mass transfer coefficients [16], [17]. The authors have found a limited number of publications on CFD modelling of air-flow through cold store openings [2], [18], [19], [20].

Validation of these CFD models has been carried out using a number of different experimental methods. Vane anemometers have been used to measure velocity across the entrance [6], [21]. The problem with this method is that the vane anemometer is not accurate where the flow is not aligned with the vane axis. Laser Doppler anemometry has also been used [21], this method allows measurement of the flow direction and velocity but is unable to measure at multiple points simultaneously.

Tracer gas techniques can been used to measure the infiltration through a cold store. There is a standard tracer gas technique [22] applicable with many types of tracer gas. Sulphur hexafluoride (SF_6) has been used successfully [1], [9] to measure infiltration. Carbon Dioxide is another gas which can be used, its disadvantage over SF_6 is that it can only be detected at much larger concentrations, however its advantage is that it can be detected with infra-red absorption equipment rather than the much more expensive electron capture gas chromatograph.

The first aim of this paper is to compare the accuracy with which the analytical models predict the infiltration through different size cold storage doors and at different cold storage temperatures against measurements using CO_2 tracer gas. The second aim is to compare CFD predictions against the measurements and establish whether CFD has any benefits over the analytical models.

This work has been part of a government/industry funded LINK project in the UK on infiltration during door openings.

2. Materials and methods

2.1 Test room and temperature measurements

Experimental studies were carried out on a cold store with internal and external temperature sensors (internal dimensions 4.8 x 5.8 x 3.8 m high) with a large single opening (2.3 wide x 3.2 m high) (Figure 1) [21]. Air infiltration was measured through the large opening and through smaller openings (1.36 m x 3.2 m, 1.0 m x 3.2 m and 0.43 x 0.69 m).

To create the smallest opening, a polythene sheet was used to block the entire opening except a 0.43 x 0.69 m region in the bottom corner of the entrance.

The thickness of the door frame was 0.16 m. The internal temperature sensors were within $\pm 1.0^{o}$C before the door was opened and an experiment started, the external within 20 ± 2.0^{o}C before the door was opened and an experiment started.

2.2 Measurement procedure

To determine the volume of air exchange in the test room during a period with the door open, the concentration of CO_2 was recorded before and after a set door opening time. CO_2 was released into the room and mixed using the evaporator fans to give a concentration of approximately 0.5% (5 000 ppm). This was measured using a CO_2 infra-red analyser (accuracy 5% of full scale).

Immediately prior to each door-opening test, the evaporator fans were switched off to allow the air movement to settle for 30 s. The door was fully opened for the set door opening time and then closed. All trials were carried out with an initial cold room temperature of -20°C.

Additional trials were also carried out with the 1.36 m wide door and initial cold room temperature of 0°C.

The concentration of CO_2 immediately before opening the door and immediately after closing the door were used to calculate the infiltration rate.

$$I = \frac{V}{t} \ln\left(\frac{C_1}{C_2} \right) \tag{1}$$

2.2.1 Door opening time

The door was left fully open for times of 10, 20, 30 and 40 s. The 2.3 m wide door took a total of 8 (±1) s to open and close, the 1.36 m and 1.0 m door took 6 (±1) s and the 0.43 m wide door opening interval was so short as to be considered insignificant.

2.3 Analytical models

Five analytical models were investigated and are described in the following sections;

2.3.1 Brown and Solvason (1963)

This model assumes a neutral level in the doorway at which the pressure inside the store is equal to the pressure outside. The major assumption used, is that the height of the neutral level is half the height of the doorway. The model is expressed as;

$$I = 0.343\, A\, (gH)^{0.5} \left[\frac{(\rho_i - \rho_o)}{\rho_{avg}} \right]^{0.5} \left[1 - 0.498 \left(\frac{b}{H} \right) \right] \tag{2}$$

2.3.2 Tamm (1966)

Tamm improved the Brown and Solvason model by calculating the height of the neutral level and using ρ_i instead of ρ_{avg}. The model is expressed as;

$$I = 0.333\,A\,(gH)^{0.5}\left[\frac{(\rho_i - \rho_o)}{\rho_i}\right]^{0.5}\left(\frac{2}{1+(\rho_o/\rho_i)^{0.333}}\right)^{1.5} \qquad (3)$$

2.3.3 Fritzsche and Lilienblum (1968)

Fritzsche and Lilienblum, who conducted experiments using vane anemometers, added a correction factor to Tamm's equation. The correction factor takes into account the contraction of the flow, friction and thermal effects. The correction factor given is expressed as;

$$K_{f,L} = 0.48 + 0.004(T_o - T_i) \qquad (4)$$

The model is expressed as;

$$I = 0.333\,K_{f,L}\,A\,(gH)^{0.5}\left[\frac{(\rho_i - \rho_o)}{\rho_i}\right]^{0.5}\left(\frac{2}{1+(\rho_o/\rho_i)^{0.333}}\right)^{1.5} \qquad (5)$$

2.3.4 Gosney and Olama (1975)

Fritzsche and Lilienblum's equation assumed that the volume flow rate into and out of the room were the same. This is only the case if the air entering the room does not cool. If it does cool then the volume flow rates will not be the same, however, the mass of air in the cold store will remain constant because both the volume and density of air inside the room remains constant. Gosney and Olama provided an equation for constant mass flow rate and by fitting measurements with their model provided a different coefficient. This means that (ρ_o/ρ_i) has changed to (ρ_i/ρ_o) in the following equation;

$$I = 0.221\,A\,(gH)^{0.5}\left[\frac{(\rho_i - \rho_o)}{\rho_i}\right]^{0.5}\left(\frac{2}{1+(\rho_i/\rho_o)^{0.333}}\right)^{1.5} \qquad (6)$$

2.3.5 Pham and Oliver (1983)

Pham and Oliver conducted experiments on air flow through cold store doors and produced a factor of 0.68 which should be applied to Tamm's equation to fit their experimental data, this new equation they called Tamm's modified equation and is shown below;

$$I = 0.226\, A\, (gH)^{0.5} \left[\frac{(\rho_i - \rho_o)}{\rho_i} \right]^{0.5} \left(\frac{2}{1 + (\rho_o / \rho_i)^{0.333}} \right)^{1.5} \qquad (7)$$

2.4 CFD model

A predictive model of the experimental test room was created using CFX 5.4 (CFDS, AEA Technology), a commercially available CFD code. A predictive model of the test room and its entrance was created [21].

To simplify the model, a number of assumptions were made;

i. There was no heat flow through the walls of the test room.

ii. The test room had no thermal mass.

iii. Humidity had no effect on the flow rate through the door (It will, however, have an effect on heat transfer through the door).

iv. How the door was opened did not affect the air-flow through it.

v. The simplification of outside room conditions had no effect.

vi. The room was leak proof i.e. air could only move through the entrance.

A tetrahedral mesh was created and then refined until a converged solution was obtained. Turbulence was modelled using the k-ε (k-epsilon), this is the industry standard two-equation turbulence model. The final mesh size varied depending on the size of entrance but varied between 95 000 and 250 000 tetrahedral elements and 18 000 and 46 000 nodes.

Predictions were obtained for the cases that were measured in the proceeding sections; three different sizes of entrance and two different initial room temperatures.

Assumption v. (The simplification of outside room conditions has no effect) was checked by extending the domain of the model from 3 m to 6 m outside of the walls of the cold room. Due to the extra memory and computing time required this was only carried out at one condition (2.3 m wide entrance). This is referred to as the large boundary model. In reality the cold room was not contained within exterior walls 3 or 6 m beyond the cold room walls, the geometry was much more complex and difficult to model. Extending the domain showed what effect this simplistic assumption had on the predictions.

Assumption vi. (The room is leak proof i.e. air can only move through the entrance) was checked by measuring the background leakage rate from the refrigerated test room with the door closed.

2.5 Door opening time

All of the above models simulate the flow through a fully open door and do not take into account the flow when the door is opening and closing. Chen et al [1] showed by experiment that the air flow through the door while it was opening and closing was equivalent to the air flow if it had been fully open for half of the time required to open or close. Therefore, the time that the door was open in the models (both analytical and CFD) was equal to the time the door was fully open plus half the time taken to open and close the door, in the experiments.

3. Results and discussion

3.1 Infiltration measurements

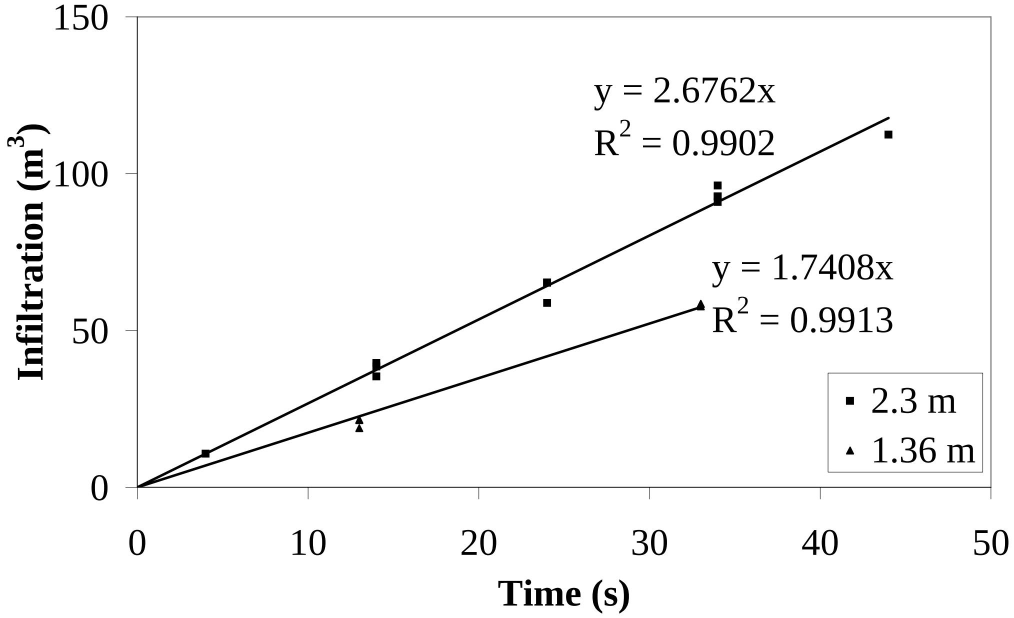

Figure 3 shows the relationship between infiltration and door opening time for both the 2.3 m and 1.36 m wide entrance. Straight lines have been fitted to the data (using the least squares method) and have been forced through zero, as there will be zero flow before the door is opened. The correlation coefficient (r^2) for the 2.3 m and 1.36 m wide entrance were 0.990 and 0.991 respectively, giving very good agreement between the measured data and the fitted straight lines. The rate of infiltration is given by the slope of the line. In the case of the 2.3 m wide door the infiltration rate is

2.68 ± 0.07 m^3s^{-1} with a 95% confidence interval.

In the case of the 1.36 m wide door the infiltration rate is

1.74 ± 0.08 m^3s^{-1} with a 95% confidence interval.

The other size entrances have measurements at only one time. It is very unlikely that reducing the size of the entrance would cause the fit to deviate from a straight line because the major reason for a non-constant infiltration rate is the change in air temperature with time, for the smaller entrances this temperature change is much smaller. We can therefore assume that they are also a straight line fit going through zero. The infiltration rates measured for all of the experiments are shown in Table 1.

3.2 Leakage of the room with door closed

The leakage rate measured was 0.0017 m^3s^{-1}. The analytical and CFD models assume that the room had no leakage. It is difficult to assess what effect this leakage will have on the infiltration. If the leakage is through the door seals then it should have no effect, as there will be no leakage when the door is opened. If the leakage is coming from elsewhere it could compound the infiltration through the door by creating a through flow, equivalent to opening two doors in the room. If this is the case then it should increase the infiltration above what is predicted. The level of leakage is much smaller than the infiltration through the door and so would not be expected to have a large effect.

3.3 Measurements compared against analytical predictions

The infiltration rates predicted by the analytical models are shown in Table 2. The percentage errors between the analytical model and the measurements are shown in brackets. A positive percentage means the predictions are higher than those measured. Values in bold are predictions that fall within the 95% confidence interval.

The Brown and Tamm models substantially over predict the infiltration for all of the measurements (between 52.1% and 122.7% over prediction). Tamm's modified model predicts the measurements much more closely than the original, (it is within experimental error for the cold store at 0^oC). The Fritzsche and Gosney models give the closest predictions; for the 1.0 m wide door, the models predict the infiltration to within experimental error (an over prediction of 6.5%). Taking all of the experiments into account, the Gosney model performed better (maximum of 38.6% over prediction) than the Fritzsche model (maximum of 43.2% over prediction).

3.4 Temperature rise inside and outside the cold store

During opening of the 2.3 m wide door, the temperature inside the cold store rose dramatically (Figure 4). With a door opening for 30 s the temperature inside the room at 2 m height rose from –20^{o}C to 15.1^{o}C and the temperature at 0.5 m height rose to –12.3^{o}C. The cold store air density (which is directly related to its temperature) was one of the constants used in the analytical models. It was clearly not constant but varied significantly once the door was open.

During 30 s door opening tests of the 0.43 m wide door, the temperature inside the cold store rose much less (at 2 m height the temperature rose from –20^{o}C to a maximum of –2.1^{o}C and the temperature at 0.5 m height rose to a maximum of –16.0^{o}C.

3.5 Measurements compared against CFD predictions

The infiltrations measured and predicted using CFD for the 2.3 m wide entrance are plotted against time in Figure 5 for both the standard and large boundary models. The large boundary model predicts a higher rate of infiltration than the small boundary model.

Both CFD models do not predict a constant infiltration with time; instead, the predictions can be split into three separate regions (Figure 6). The first region is the lag region; this is because of the time the flow takes to fully develop. The second region is the steady state region; this is where there is a constant flow rate through the entrance. The final region is the tail off; where the temperature difference (driving force) between the cold store and the surroundings is reducing.

The steady state region has a higher infiltration rate for the large boundary model. This is because the closer boundary restricts the infiltration. The lag phase is more defined for the smaller boundary, this is probably due to the temperature of the region outside the cold store getting warmer quicker and therefore reducing the temperature difference between the cold store and the surroundings.

Table 3 shows the following predicted parameters from the CFD models: The infiltration rate (from the steady state flow rate region), the lag time (the time that the straight constant flow line cuts the time axis) and the drop off time (time at which predictions deviate from constant flow line) predicted by the CFD models.

The lag region was predicted to be between 0.3 and 1.6 s for the different models. This lag phase has been measured by Azzouz et al [23] to be of the order of 1.5 s. For long door opening times of 30 s, a 1.5 s lag time will reduce the infiltration by only 5%, while for shorter door opening periods of, for example 10 s, it will reduce the infiltration by 15%.

The infiltration rate defined by the steady flow rate region, over predicted the infiltration for all conditions (between 13.4% and 42.5%). The CFD predictions were always better than those from the Brown and Tamm equations, but were always worse than predictions by the Gosney equation.

With the exception of the 0.43 m wide entrance, the predicted drop off region was within the door opening times for all experiments.

4. Conclusions

The first aim of this paper was to establish whether analytical models could be used to predict the infiltration through different size entrances of our cold store and different initial cold store temperatures.

The Gosney model was the best of the analytical models and was able to predict the infiltration for two of our experiments within experimental error. The Gosney model over predicted the infiltration for the other experiments and was worst for the 0.43 m wide door.

The analytical predictions were better for the 2.3 m wide door than the 0.43 m wide door. This was not as expected because the assumption in the analytical models was that the temperature difference between the cold store and ambient is constant. This was reasonably valid for the 0.43 m wide door but not for the 2.3 m wide door. The inaccuracy for the 0.43 m wide door was probably because the coefficients measured by the analytical modellers were not valid for such a small entrance. From the point of view of the refrigeration engineer this is not important, as this entrance size is too small to be of practical interest.

The second aim was to establish whether CFD could provide better predictions than the analytical models.

The volume of air contained in our cold room was such that, with the exception of the 0.43 m wide entrance, all trials caused appreciable temperature rises within the room during the door-opening period. The initial lag time was a small but a significant proportion of the total door open time (e.g. 15% for 10 s door open). These factors were not included in the analytical models and were therefore expected to make the analytical predictions inaccurate. As the CFD predictions are able to take into account these factors, the CFD predictions were expected to be more accurate.

The initial CFD predictions showed that the infiltration was not constant with time and that there were three regions (lag, constant flow rate and drop off).

There were no detailed measurements taken during the lag region, so we were unable to confirm the CFD predictions of the lag time, however, previous authors [23] have confirmed that it does exist and is of the same order as predicted by the CFD.

The CFD predicted infiltration rate is higher than the measured values in all cases. Modelling an extended boundary makes this over prediction even greater. Laser Doppler anemometry (LDA) measurements presented by Foster et al [21] showed that the velocities close to the side of the door were low due to separation of the airflow at the sharp corners of the door-frame pillars. This contraction was not apparent from the CFD predictions because the size of the grid was not small enough in this region to predict this (Figure 7).

A drop off region of the order predicted by CFD was not apparent during the door opening times measured. The reason for this may lie in the inaccuracy of the CFD predicted infiltration rate. As the predicted flow rate was higher, we would expect the predicted drop off to occur earlier.

CFD predictions were a significant improvement in accuracy over the fundamental analytical equations (Brown and Tamm), however, the empirical coefficients added by Gosney and Fritzsche gave a more accurate prediction than the CFD. A more detailed CFD model with more grid cells in the entrance would most likely calculate a better prediction, but due the need to model the room and its surroundings and limited computing resources this was not possible. The ability to model the lag time and the drop off region would have put the CFD predictions at an advantage for very short and very long door opening times respectively. CFD allows factors such as the effect on the infiltration to temperatures inside and outside of the room to be investigated. It also allows the effect of air curtains on the entrances to be investigated. It is these benefits that will be investigated and presented in a future paper.

5. Acknowledgements

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The authors would also like to thank Paola D'Agaro from the University of Udine (Italy) who helped in the latter stages of the project to gather the data.

6. Nomenclature

A	cross sectional area of entrance, m^2
b	thickness of door frame, m
C_1, C_2	initial and final concentration of CO_2 in the room, %
g	acceleration due to gravity, 9.81 m s^{-2}
$K_{f,L}$	Correction factor, dimensionless
H	height of entrance, m
I	Infiltration rate, m^3 s^{-1}
t	time, s
T_o, T_i	temperature outside and inside colds store, ^oC
V	volume of air within the room, m^3

Greek letters

ρ_i, ρ_o, ρ_{avg}	density inside and outside cold store and average, kg m^{-3}

Figure 1. Cold store with a large single opening constructed inside a processing hall at FRPERC, University of Bristol.

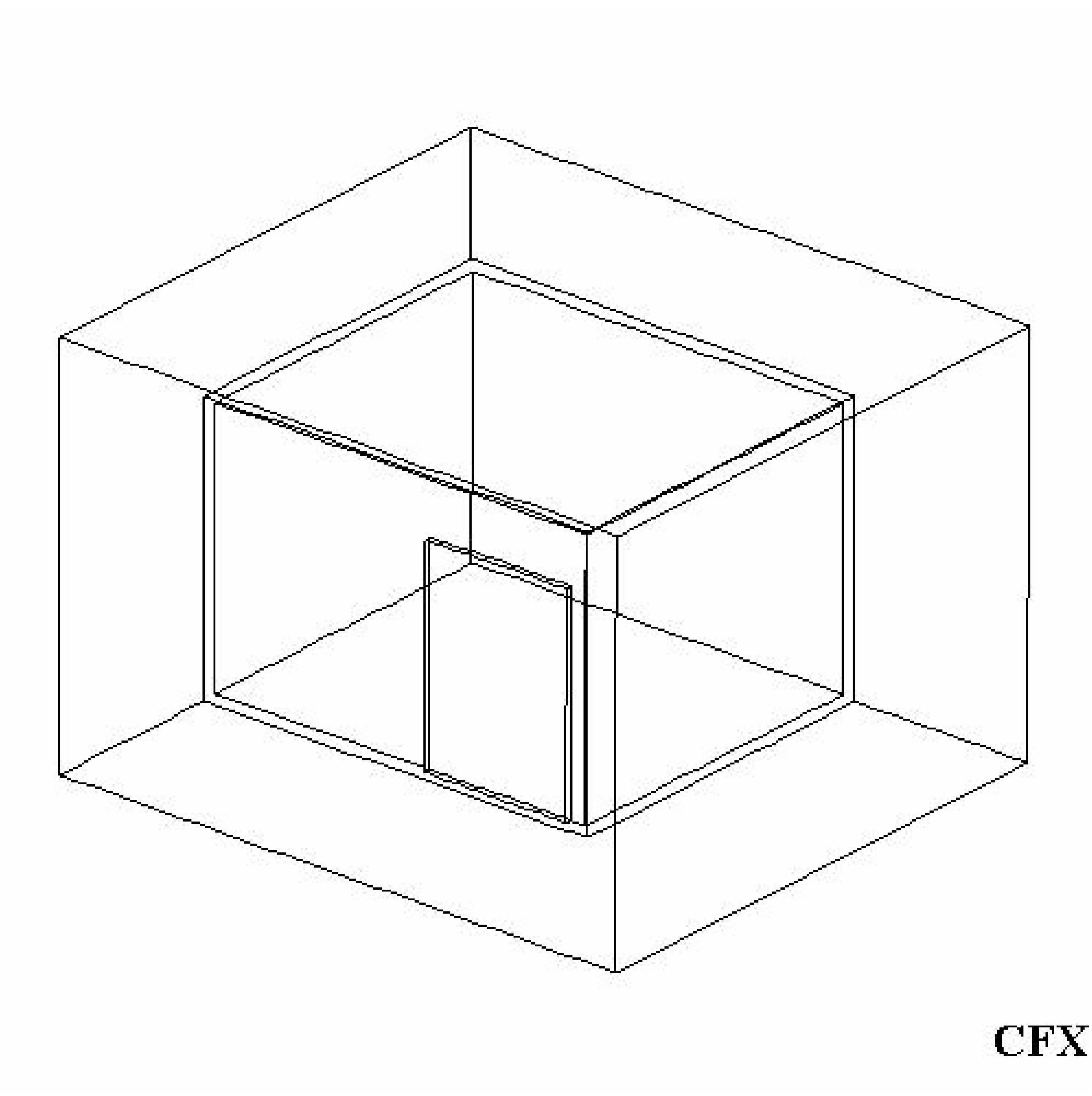

Figure 2. Geometry of the test room and its outer boundary used for the CFD model.

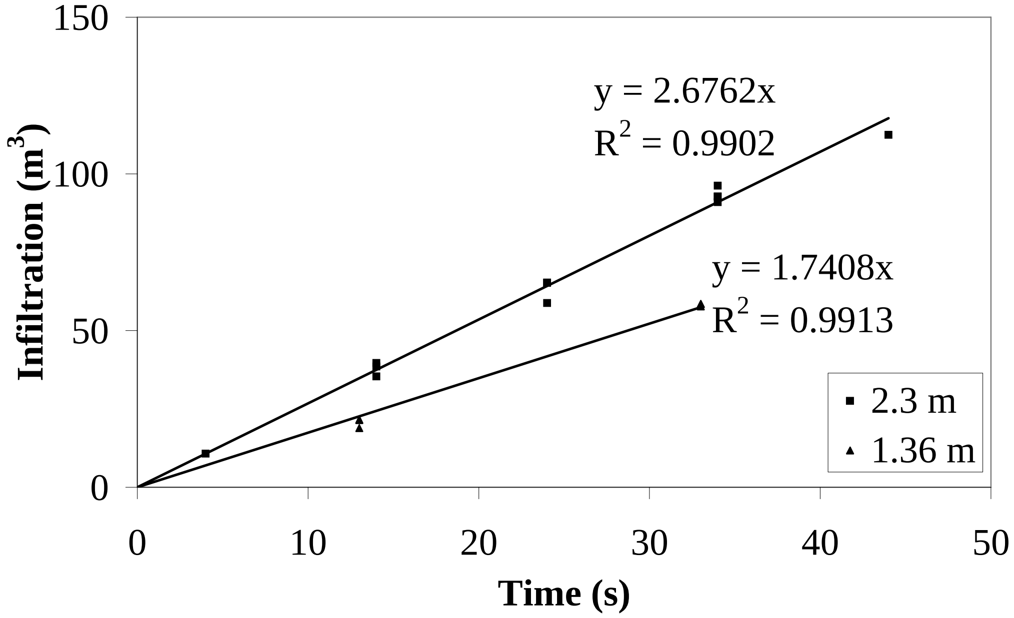

Figure 3. Relationship between infiltration and door opening time for both the 2.3 m and 1.36 m wide entrance. Straight lines have been fitted to the data and through zero.

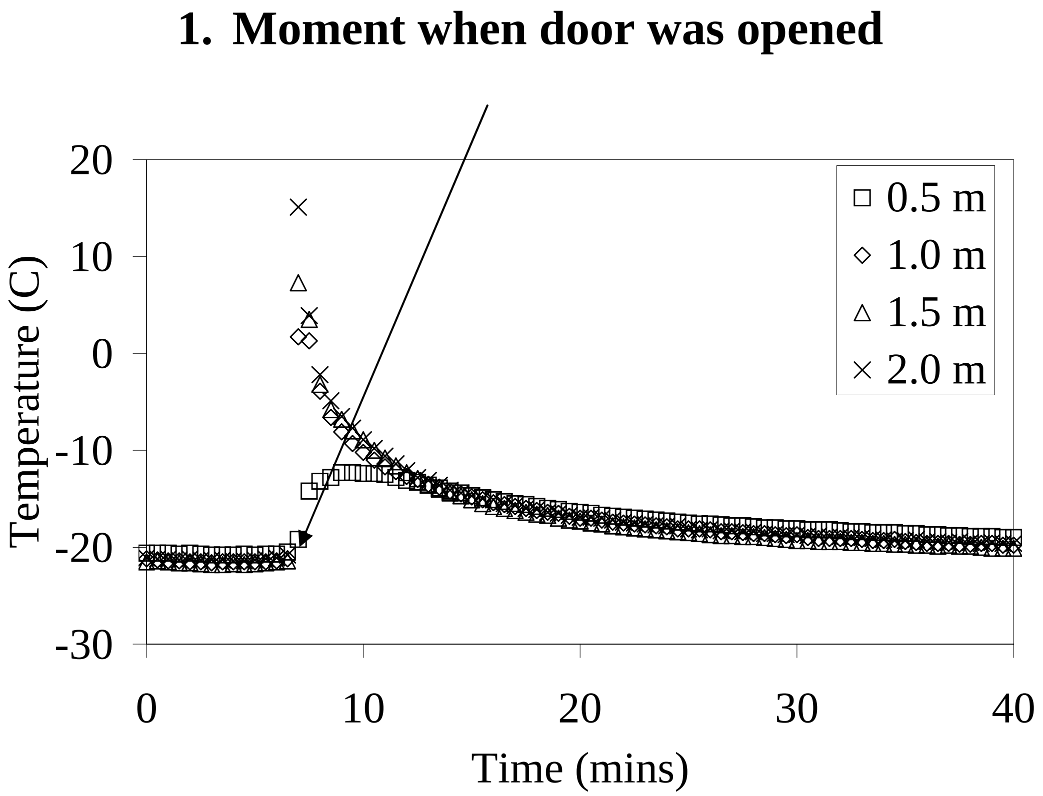

Figure 4. Temperatures within the cold store at different heights from the floor before, during and after door opening of the 2.3 m wide entrance.

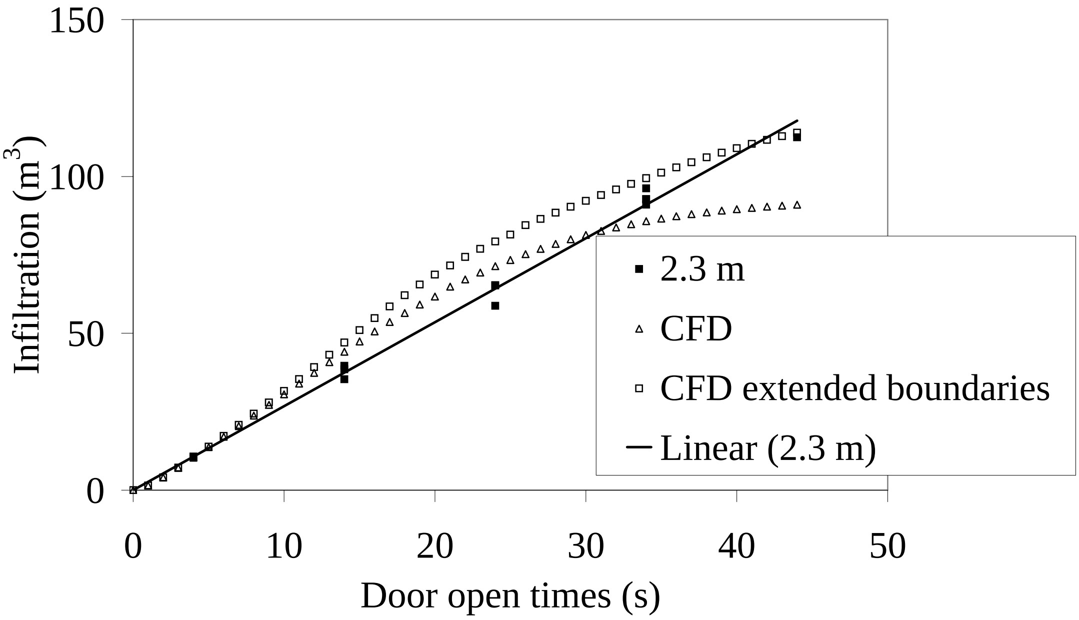

Figure 5. Measured and predicted infiltration through the 2.3 m wide door for different door opening times. The CFD predictions are for both the standard and large boundary models.

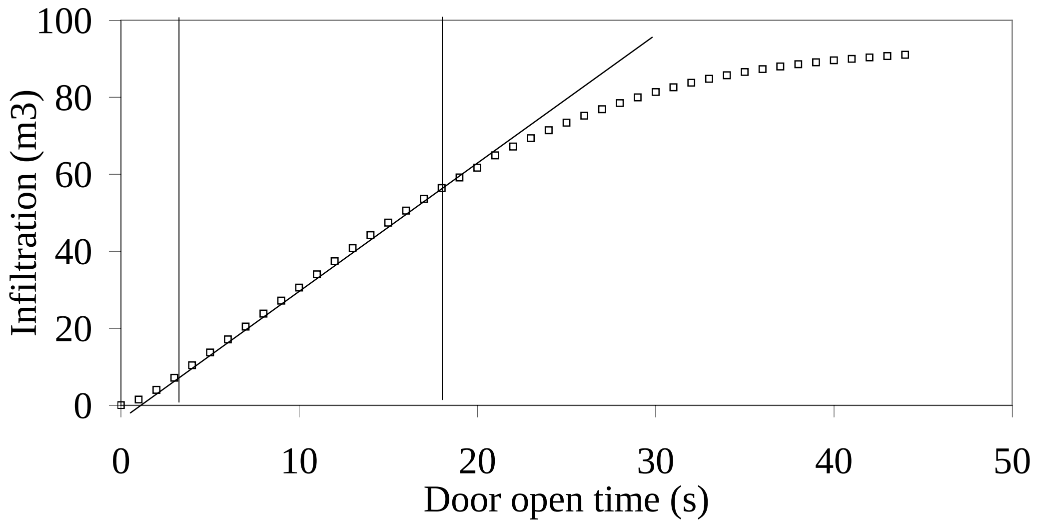

Figure 6. Predicted infiltration for the 2.3 m wide entrance for different door opening times.

The prediction is split into three different regions.

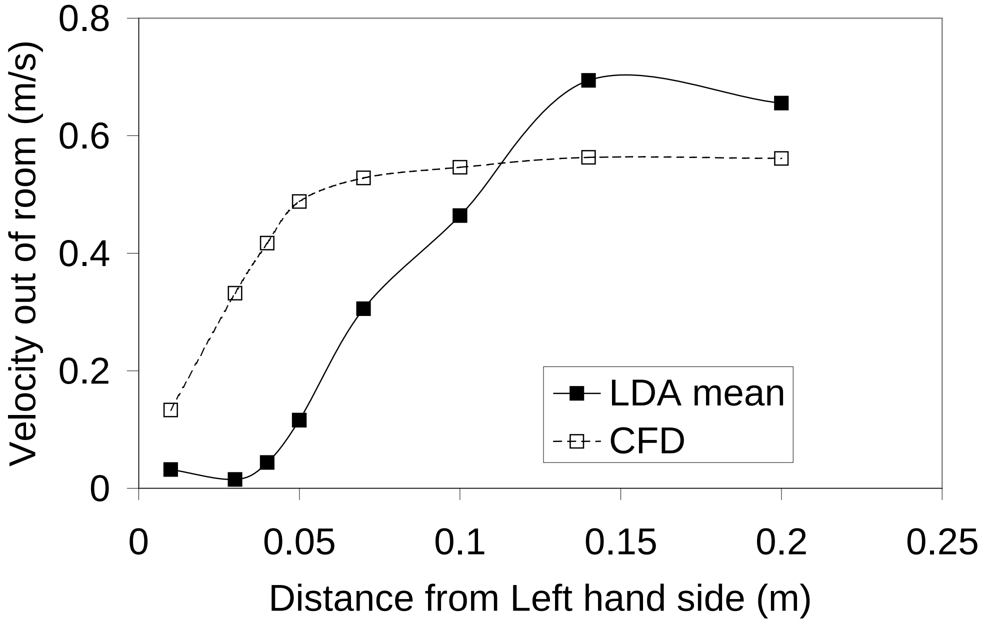

Figure 7. Velocities (direction perpendicular to the face of the entrance) measured and predicted through the 0.43 m wide entrance 20 s post door opening using the LDA plotted against distance from the vertical door frame. Measurements and predictions are made 0.132 m from the floor and in a plane that cuts through the middle of the door frame.

Door width (m)	Door height (m)	Cold store temperature (^oC)	Measured infiltration rate ± 95% confidence interval (m^3s^{-1})	error (± 95% confidence interval) %
2.3	3.2	-20	2.68 ± 0.07	2.6
1.36	3.2	-20	1.74 ± 0.08	4.6
1.36	3.2	0	1.42 ± 0.15	10.6
1.0	3.2	-20	1.38 ± 0.09	6.5
0.43	0.69	-20	0.044 ± 0.005	11.4

Table 1. Measured infiltration rates for all of the experiments and their 95% confidence intervals.

Door width (m)	Door height (m)	Cold store temperature (^oC)	Infiltration rate predicted by the analytical models (m^3s^{-1}). Prediction error is in brackets (%)				
			Brown	Tamm	Fritzsche	Gosney	Tamm modified
2.3	3.2	-20	5.28 (97.0)	5.26 (96.3)	3.37 (25.7)	3.24 (20.9)	3.58 (33.6)
1.36	3.2	-20	3.12 (79.3)	3.11 (78.7)	1.99 (14.4)	1.92 (10.3)	2.11 (21.3)
1.36	3.2	0	2.17 (52.8)	2.16 (52.1)	1.21 (-17.4)	**1.38 (-2.9)**	**1.47 (3.5)**
1.0	3.2	-20	2.30 (66.7)	2.29 (65.9)	**1.46 (5.8)**	**1.41 (2.2)**	1.56 (13.0)
0.43	0.69	-20	0.090 (104.5)	0.098 (122.7)	0.063 (43.2)	0.061 (38.6)	0.067 (52.3)

Table 2. Predicted infiltration rates using the analytical models. Percentage over prediction is shown in brackets (predictions within experimental error are shown in bold).

Door width	Door height	Cold store temperature	Infiltration rate predicted by the CFD models Prediction error is in brackets	Lag time	Drop off time
(m)	(m)	(^{o}C)	(m^3s^{-1}) (%)	(s)	(s)
2.3	3.2	-20	3.36 (25.4)	0.7	17
			* 3.82 (42.5)	* 1.5	* 18
1.36	3.2	-20	2.28 (31.0)	1.2	20
1.36	3.2	0	1.61 (13.4)	1.6	29
0.43	0.69	-20	0.059 (34.1)	0.3	>30

- large boundary model

Table 3. Infiltration rate, lag time and drop off time predicted by the CFD models.

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