A Case Study of Far-Field Temperatures in Progressing Fires

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ABSTRACT

The non-uniform conditions and potential progression of fires in larger spaces calls for modelling methods extending outside of the traditional compartment fire framework. Even though a handful of studies in the area exist there is still little guidance available on how progressing fires in large enclosures can be modelled. Three different methods to calculate far-field gas temperature in large enclosures are therefore reviewed in this paper with the help of a case study. The three methods used are: the analytical Alpert ceiling jet correlation, the Fire Dynamics Simulator (FDS) and a Multi-Layer Zone (MLZ) model.

The enclosure used in the case study is intended to represent a large open space, i.e. an office, warehouse or supermarket. Two different user defined fire scenarios, which represent two progressing fires, are analysed. This is a comparative study and no experimental data is used to evaluate the models. However, it is considered reasonable to believe that FDS gives good predictions since it has shown to predict gas temperatures well in previous validation studies. The MLZ model has not been thoroughly evaluated, but it has been seen to overestimate experimental results slightly in a previous study.

The results from FDS and the MLZ model show that there is a temperature distribution (vertical and horizontal) in both fire scenarios, which means that there are non-uniform conditions in the gas layer. The results also indicate that there is a correspondence between the MLZ model and FDS; however, as the heat release rate increase the difference between the models increases. The analytical correlation results in much lower temperature predictions than both FDS and the MLZ model. The main reason for that is that the correlation assumes the flow to be unconfined, which is not the case in this study.

The main benefits of the MLZ model is the low computational time (about 1 minute on a laptop computer) compared to FDS (where the computational time was more than two days). Furthermore, the MLZ model provides temperature profiles both horizontally and vertically, which is not the case in conventional zone models.
INTRODUCTION

The turbulence caused by a fire will mix the hot gases in a small enclosure and the properties (like temperature and visibility) of the hot gas layer will be rather uniform both in the vertical and horizontal direction. This makes it possible to derive equations and find correlations for calculating e.g. gas temperatures. The first comprehensive work on this, so-called “compartment fire framework”, was done by Kawagoe in the 1950s [1]. A lot of effort has been conducted within the area since then and the compartment fire has proven to be a robust and simple way of describing fire conditions under certain circumstances.

The time-temperature curves for post-flashover fires in Eurocode 1 [2] are based on the uniform temperature assumption, which is reasonable because the experimental tests that the method is based on were conducted in rather small enclosures. The situation becomes more complex in large enclosures where the hot gas layer cannot be regarded as uniform. For instance, it is not likely that flashover will occur in large enclosure in the same way as expected in the compartment fire framework. In the compartment fire framework the fire is fuel controlled and grows, at a certain time point the heat flux on the combustibles in the room is so intense that flashover occurs. Then all combustible material is involved in the fire and it becomes ventilation controlled, e.g. the heat release rate is controlled by the supply of oxygen. The terms regime I and regime II [3] are sometimes used to distinguish between ventilation controlled and the fuel controlled burning, respectively. It has been argued that fires in large spaces are likely to be within regime II [3][4], since the availability of air most likely will be high due to the presence of large openings and leakages in the boundaries. Traditional methods for calculating heat release rates in ventilation controlled fires are therefore inappropriate to use in larger enclosures where the fire progresses or travels, as it is termed by e.g. Stern-Gottfried and Rein [4].

That fires can progress in a large enclosure have been documented [4][5] and there are some examples when this have been studied in fire tests [5]. Kirby et al [6] did burns in a 23 m by 6 m enclosure and saw that flashover did not occur as according to the compartment fire framework, instead it progressed between fuel packages. Hidalgo et al [7] have recently presented an experimental study undertaken to characterise fires in large spaces. A dozen fire tests were performed Hidalgo et al in an 18 m by 6 m enclosure. A complete analysis of the data have not been published yet but the setup was well equipped with different types of sensors and the data from the tests will definitely add to the knowledge of enclosure fire dynamics in large spaces.

The non-uniform conditions and potential progression of fires in larger spaces calls for modelling methods extending outside of the compartment fire framework. Stern-Gottfried and Rein [4] presents the so-called traveling fires framework in which the thermal field induced by the fire is divided into two regions: the near field and far-field. The position and size of the regions are relative to the position of the fire, and moves within the enclosure as the fire progresses. The near field is the burning region of the fire, and the far-field is the region where no burning or flames are present, instead the smoke layer will provide a thermal exposure. The near field temperatures can be modelled with methods like the localised fire in Eurocode 1 [2] or with a worst case flame temperature of e.g. 1200°C as proposed by Stern-Gottfried and Rein. The far-field temperature is considered to be more challenging to model.

Rein et al [8] used the Computational Fluid Dynamics (CFD) model Fire Dynamics Simulator (FDS) to model the far-field temperatures but found it problematic due to the high computational cost. Therefore, later efforts to estimate far-field temperatures have focused on using the much simpler analytical methods like the ceiling jet correlation by Alpert [9]. Alpert assumed an axisymmetric fire plume beneath a flat, horizontal ceiling, unobstructed by walls and derived correlations for the ceiling jet temperature and velocity. The ceiling jet correlations are generally good for estimating gas temperatures in the early stages of fire. The problem with applying the Alpert correlation is that it is not applicable in an enclosed space when a hot gas layer, which will affect the ceiling jet temperature, forms. Furthermore, in the original work by Alpert [9] it was seen that at distances of 3 to 5 ceiling heights from the centre of the fire, the heat transfer to the ceiling were significant and this is not treated directly in the correlation. More recently promising efforts have been made by the research group in Edinburgh [5] to couple a model for localized fires with a simple zone model; however, the work is currently said to be on a conceptual stage.

Even though a handful of studies in the area exist there is still little guidance available on how progressing fires in large enclosures can be modelled. Three different methods to calculate far-field gas temperature in large enclosures will therefore be reviewed in this paper with the help of a case study.
APPLIED METHODS

The three methods used to calculate far-field temperatures are, the analytical Alpert ceiling jet correlation, a CFD model and a Multi-Layer Zone (MLZ) model.

Analytical model

Analytical models to estimate velocities and temperatures in ceiling jets have existed since at least the 1970s [9] but a continuous improvement and development have been done since then (see e.g. [10] and [11]). A ceiling jet is created when the buoyancy driven fire plume impinges on a ceiling and the hot gases spreads radially under the ceiling. The temperature in the ceiling jet will decrease as it moves away from the plume centreline due to entrainment of cold air and heat losses to the ceiling. If the ceiling jet is unconfined it will have a maximum thickness of about 5-13% of the total room height [12]. In a normal compartment fire this type of unconfined ceiling jet will only exist in the earliest stages of fire development before the hot gases accumulate in the compartment. Therefore, these types of models are normally used to estimate sprinkler and heat detector activation in pre-flashover fires. The Alpert ceiling jet correlation [9] (see Equation 1) is used in this paper since it's been proposed to be used for modelling far-field temperatures [4]. In Equation 1, \( \dot{Q} \) is the fire heat release rate, \( r \) is the radial distance from the plume centreline and \( H \) is the height to the ceiling.

\[
T_g - T_a = 5.38 \left( \frac{\dot{Q}}{r} \right)^{2/3} \frac{H}{r} \tag{1}
\]

CFD model

FDS developed by NIST [13], is often used in fire safety engineering. FDS is a CFD model where fire-driven fluid flows are simulated. The software solves the Navier–Stokes equations numerically with an emphasis on heat and smoke transport.

MLZ model

The MLZ concept has been described in previous publications [14][15]; therefore, no detailed description of the concept is therefore given in this paper. The conservation of mass and energy is used in zone models to calculate hot gas temperatures and flows between different zones are calculated with the help of pressure differences and the Bernoulli equation. The MLZ model uses these zone model principles. However, in contrast with the more established two-zone models (like CFAST [16]) where each room consists of two zones, each enclosure is divided into several regions (horizontal) and layers (vertical) in the MLZ model. This means that the enclosure is divided in to several smaller zones. The fire is specified as a heat release rate and the heat and hot gases rises upwards from the fire in a plume that enters the highest located layer in the fire region. Air and hot gases is also entrained in the plume from the layers that it passes through. Mass is transported horizontally to layers in adjacent regions due to hydrostatic pressure differences. There is also a flow of mass vertically between layers in each region, which is calculated based on the conservation of mass. Heat losses to boundaries and radiation between cells are also calculated. The MLZ model used in this paper extends in three dimensions and is based on the model used by Johansson [17]. Johansson made a minor evaluation study of the model and saw that it over predicted measured temperatures slightly.

ANALYSIS

The enclosure used in the case study is fictive and it is constructed to represents a large open space, i.e. an office, warehouse or supermarket. The enclosure is 20 m x 32 m x 4 m with one door (12 m x 3 m) that is placed in the middle of one of the short ends (see Figure 1 and Figure 2). The boundaries are made of 0.1 m thick lightweight concrete. Two measurement points (M1 and M2) are used in this analysis and both are placed in an area that is regarded as the far-field, e.g. no expected flames or combustion.

Design fires

Two simple well-defined fire scenarios are used in this study. The fuel load density determines the duration of fire in each fuel package. Two design fire scenarios that represent two progressing fires are modelled with the three methods. The first design fire scenario consists of four different fuel packages (each 2 m by 2 m large, see Figure 1) where each package burns according to a Fast (0.047 kW/s²) alfa-t² during 235 seconds up to 2.6 MW. Fuel package 2 is ignited 120 seconds after fuel package 1, fuel package 3 is ignited 240 seconds after fuel package 1 and fuel package 4 is ignited 360 seconds after fuel package 1. Each fuel package has a fuel load density of 500 MJ/m²; this results in that each fuel package burns out 920 seconds after ignited. The distance between each fuel package is 2 m. The second scenario includes nine fuel packages (see Figure 2)
that are identical to the fuel packages in scenario 1. The nine fuel packages ignite every 120 seconds according to the sequence presented in Figure 2. The distance between the fuel packages is 2 m.

Figure 1: Layout of scenario 1 (left) and resulting total heat release rate from the four fuel packages (right).

Figure 2: Layout of scenario 2 (left) and resulting total heat release rate from the nine fuel packages (right).

Setup of the models

The distance \( r \) in Alpert ceiling jet correlation (Equation 1) was taken as the distance to the location of the weighted average of the total heat release rate. Five different meshes were used in FDS, and a mesh size of 0.1 m was used around the fuel packages and 0.2 m in the rest of the domain. A total of 584,000 cells were used in scenario 1 and 2 while 1,200,000 cells were used in scenario 3. The enclosure was divided into 40 regions in the MLZ model and each region was divided into 8 layers, i.e. 320 cells in total.

Results

No effort is made here to compare the calculation times in detail. Even so, it is considered worth mentioning that the MLZ simulations were performed in less than 1 minute on a laptop computer while the FDS simulations took more than 60 hours each to perform on the LUNARC cluster [18]. The results are presented for different elevations at M1 in Figure 3, and as vertical temperature profiles in Figure 4-5. The results at measurement point M2 indicate similar trends as in Figure 3-5. Results from simulations with CFAST [16] are included in Figure 4-5 for reference.

Figure 3: Temperatures in M1 in scenario 1 (left) and scenario 2 (right).
FDS and the MLZ model clearly show that there is a vertical temperature distribution that is not possible to catch with the two-zone model like CFAST (see Figure 4 and Figure 5). Based on the results it can be seen that there is a correspondence between the MLZ model and FDS; however, as the heat release rate increases (as in scenario 2) the difference between the models increases. It is also clear from Figure 3 that the simple analytical formula by Alpert gives much lower temperatures than the numerical models.

**DISCUSSION AND CONCLUSION**

Three different methods to calculate far-field temperatures in progressing fires have been studied in this paper. No experimental data are available for the case analysed; consequently, it is not possible to state how accurate the methods are in predicting far-field temperatures. Even so, it is reasonable to believe that FDS gives reasonable predictions since it has shown to predict gas temperatures well in previous validation studies [13]. However, when it comes to fully developed fires it has been seen that FDS can under predict temperatures [19][20]. The major drawback of FDS in this study is the long calculation time.

The results from both FDS and the MLZ models indicate that there is a vertical and horizontal temperature distribution, which is not possible to model with two-zone models like CFAST. The Alpert ceiling jet correlation gives a single temperature and it is much lower than the temperatures predicted by FDS and MLZ models. The main reason is that the Alpert correlation assumes the flow to be unconfined which is not the case in this study and probably seldom in any situations after the initial growth stage of a fire. If it cannot be guaranteed that the ceiling jet will be unconfined it will most likely underestimate the gas temperature.

The MLZ model that has been used in this study was verified as it was developed and written, however, the verification process has not been as thoroughly as that of FDS. Furthermore, in the previous evaluation study it has been seen that the model might overestimate gas temperatures slightly. Even so, the case study indicates that the MLZ model can estimate both vertical and horizontal far-field gas temperatures similar to FDS.

The main benefits of the MLZ model is the low computational time and that it provides temperature profiles both horizontally and vertically. It would be desirable to evaluate the MLZ model further against experimental data. The computer power available for fire safety designers is constantly improving, this means that the time
to run a CFD models is constantly decreasing, which lessens the need for a quicker and less accurate tool like the MLZ model. However, the MLZ model is simple and easy to grasp which means that users are more likely to understand what they are doing and how the model works, which can result in less mistakes and more robust designs.

REFERENCES

[1] Kawagoe, K. (1958) Fire Behavior in Rooms. Report no. 27, Building Research Institute, Japan.
[2] EN 1991-1-2 (2002) Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire. European Committee for Standardization.
[3] Torero, J.L., Majdalani A.H., Abecassis-Empis C. and Cowlard A. (2014) Revisiting the Compartment Fire. Fire Safety Science 11:28-45. http://dx.doi.org/10.3801/IAFSS.FSS.11-28
[4] Stern-Gottfried J, Rein G (2012) Travelling fires for structural design—part II: design methodology. Fire Safety Journal 54:96–112. http://dx.doi.org/10.1016/j.firesaf.2012.06.011
[5] Dai, X., Welch, S. and Usmani, A. (2017) A critical review of “travelling fire” scenarios for performance-based structural engineering, Fire Safety Journal, 91:68-578. https://doi.org/10.1016/j.firesaf.2017.04.001
[6] Kirby, B.R, Wainman, D.E., Tomlinson, L.N., Kay, T.R. and Peacock, B.N. (1999) Natural Fires in Large Scale Compartments. Int. Journal on Engineering Performance-Based Fire Codes, 1(2):43-58.
[7] Hidalgo, J.P. Cowlard, A. Abecassis-Empis, C. Maluk, C. Majdalani, A.H. Kahrmann, S., Hilditch, R., Krajcovic, M. and Torero J.L. (2017) An experimental study of full-scale open floor plan enclosure fires, Fire Safety Journal 89:22-40.
[8] Rein, G., Zhang, X., Williams, P., Hume, B., Heise, A., Jowsey, A., Lane, B. and Torero, J.L. (2007) Multi-storey fire analysis for high-rise buildings. In: 11th International Interflam, London, UK.
[9] Alpert R. (1972) Calculation of response time of ceiling-mounted fire detectors. Fire Technology 8(3):181-195.
[10] Alpert R. (2011) The Fire-Induced Ceiling-Jet Revisited. In: 5th FireSeat Symposium. Edingburgh, Scotland.
[11] Johansson, N., Wahlqvist, J. and van Hees, P. (2014) Numerical experiments in fire science: a study of ceiling jets. Fire and Materials 39(5):533-544. http://dx.doi.org/10.1002/fam.2253
[12] Karlsson B and Quintiere JG. (1999) Enclosure Fire Dynamics. Boca Raton, USA.
[13] Floyd, J., Forney, G., Hostikka, S., Korhonen, T., McDermott, R., McGrattan, K. and Weinschenk, C. (2013) Fire Dynamics Simulator Technical Reference Guide - Volume 3: Validation. NIST Special Publication 1018, National Institute of Standards and Technology, Gaithersburg, MD, USA.
[14] Suzuki, K., Harada, K. and Tanaka, T. (2002) A Multi-layer Zone Model For Predicting Fire Behavior In A Single Room. Fire Safety Science 7: 851-862. http://dx.doi.org/10.3801/IAFSS.FSS.7-851
[15] Suzuki, K., Harada, K. Tanaka, T. and Yoshida, H. (2004) An Application of a Multi-Layer Zone Model to a Tunnel Fire. In: 6th Asia-Oceania Symposium on Fire Science and Technology.
[16] Peacock, R., Forney, G., and Reneke, P. (2017) Consolidated Fire And Smoke Transport (Version 7) Volume 3: Verification and Validation Guide. NIST Special Publication 1889v3, National Institute of Standards and Technology, Gaithersburg, MD, USA.
[17] Johansson, N. (2017) Estimating gas temperatures in large enclosures. In: CONFAB 2017, London, UK.
[18] Center for Scientific and Technical Computing, LUNARC, Lund University, Sweden http://www.lunarc.lu.se/resources/hardware/aurora/
[19] Pope, N.D. Bailey, C.G (2006) Quantitative comparison of FDS and parametric fire curves with post-flashover compartment fire test data, Fire Safety Journal 41(2):99-110. https://doi.org/10.1016/j.firesaf.2005.11.002
[20] Jahn, W., Rein, G., and Torero, J.L. (2011) A posteriori modelling of the growth phase of Dalmarnock Fire Test One, Build. and Envir. 46(5):1065–1073. https://doi.org/10.1016/j.buildenv.2010.11.001