Large Eddy Simulation of the Backdraft phenomenon and its Mitigation in a Compartment Fire

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1. Introduction

A fast deflagration or backdraft is produced when into a hot, fuel-rich compartment an inflow of fresh air is allowed through an opening, then a cold gravity current is established close to the enclosure's floor flowing to the back wall of the compartment. If an ignition source is located in the proximity of flammability limits of the mixture, a sudden combustion might begin which will rapidly expand towards the opening and burst outside the compartment into a dramatic fireball. Backdraft is essentially a violent combustion process involving both premixed and non-premixed regimes.

The occurrence of backdraft continues to be a hazard that can cause the death of people and the collapse of buildings [2]. The critical condition for the occurrence of a backdraft is, therefore, of considerable importance in fire safety. As such, this phenomena has been the subject of several experimental investigation. Similarly, the prediction of the ignition time for backdraft, i.e. the elapsed time from the moment when the hatch is opened until ignition occurs, is important for people and fire fighters in order to safely leave the building. This paper reports on some recent study to develop and validate predictive methods for the backdraft phenomenon and its mitigation by water mist. The reduced backdraft tests of Weng and Fan [1] were considered.

2. Numerical Models

The simulations were conducted with the authors' modified version of the Fire Dynamics Simulator (FDS), a LES code developed by the National Institute of Standards and Technology in the USA (NIST) [2]. Non-premixed and premixed combustion regimes are two idealized scenarios, which are often mixed but conceptually very different. It is hard to construct a model that can cope with both regimes simultaneously. The premixed front is thin and propagates through the unburnt region while the diffusion flame is mixing controlled and does not propagate by itself. Assuming global single-step chemistry and neglecting radiative heat transfer, two basic control parameters are needed to capture partially premixed flames, i.e. the mixture fraction Z(x,t) and a reaction progress variable C(Z;x,t). Different expressions have been proposed for the progress variable, C. Here we adopt the formulation of Domingo et al. [3] which is valid for both premixed and non-premixed combustion. It is the exact expression for the progress variable as a function of the mixture fraction.

The flame index concept of Domingo et al. [4] is used to separate the two different combustion regimes. The index describes the structure of the flame based on fuel and oxygen gradient, allowing different combustion models to be implemented separately for the diffusion and premixed reaction zones. For non-premixed combustion, the Laminar Flamelet approach is used through the FlameMaster code of Pitsch [5]. The flame surface density approach was adopted for the premixed regime. The sub-grid wrinkling factor can be regarded as the ratio of the turbulent flame speed, $S_{T\Delta}$ and the unstrained laminar flame speed s_l^0. The sub-grid wrinkling factor is linked to Σ

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by $\Sigma = \Xi\left|\nabla\tilde{C}\right|$, where $\tilde{C}$ is either a thickened or filtered progress variable. A model based on local quantities is used for the wrinkling factor.

3. Experiments considered

The reduced scale backdraft tests of Weng and Fan [1] were considered. The compartment dimensions are (1.2 × 0.6 × 0.6) m and is fitted with a variety of end–opening geometries. A square methane burner of (0.15 × 0.15) m is placed against the end-opening wall. A downward–directed pressure nozzle is positioned 0.3 m from the end-opening wall, at 0.078m from the ceiling and 0.3m from the sidewall. Figure 1 shows the scaled compartment when a door is used as opening.

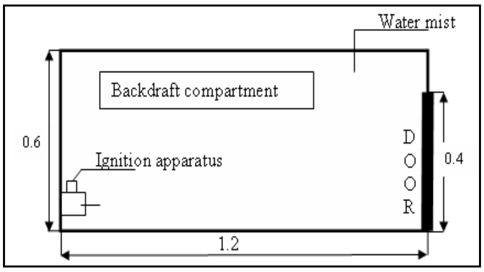

Fig. 1. Scematic of the compartment.

The flame was ignited at 0 s. As the compartment is sealed, the flame dies out due to oxygen starvation. The burner was left on injecting methane for predetermined period of time. Optionally, during this time, a known amount of water mist was injected into the compartment and allowed to vaporize and to mix with the gases. At the time of the slot opening, the fuel mass flow at the burner was shut off and the hatch was opened to allow fresh air to come into the vitiated environment. In this later process, the electrically heated metal wire was turn on and eventually, after the ignition takes place, a fast deflagration travelling towards the opening occurred.

4. Results and Discussion

The entire process can be divided into several stages. At the beginning, a well-ventilated diffusion fire is set up on the burner. Due to the lack of oxygen, the fire is shortly off while the burner is still on. Therefore, there is no more combustion in the enclosure and only mixing occurs between the fresh fuel and the products. Eventually, at this stage, the sprinkle is activated and water mist is allowed in the compartment. The mist is considered to be fully evaporated. Later on, the door is opened and a gravity current is established travelling towards the back wall. Fresh air comes into contact with hot products, unburnt fuel, water vapour and oxygen. Eventually, when the mixture reaches the flammable limits close to the ignition source a deflagration towards the opening might be produced. Here we focus on the simulation results for the last process of the experiment, namely the ignition and deflagration.

Table 1 presents the upper layer temperature (T_U), fuel (Y_F) and oxygen (Y_O) mass fractions in the upper layer for the five tests considered. In the experiment only one measuring point was located in the upper layer and this point was monitored in the simulations.

The first stage of the deflagration was relatively slow in the highly diluted environment. The combustion was initiated at the back wall leading to increased pressure. This over pressure expulsed hot products thorough the opening, which were seen as black smoke flowing outside the container. The flammable surface was usually located in the proximity of the floor; depending on the gravity current. Thus, the flame would propagate towards the opening at a close distance from the container's floor. As the pressure was measured at floor level, it was subject to the influence of relative position of the flame to the floor.

In the window case, the mixing was considerably more important than in the other two cases and then the flammable mixture volume was larger, thus the amount of ignitable fuel more important.

Table 1 Simulation and experimental results for the three different types of end openings

Opening Geometry	Run	Water mist		Specie concentrations		Compartment temperature (K)	Ignit. time (s)	Maxim pressure (Pa)	Opening total mass flow (kg)		Fire ball
		Time (s)	Mass (10^{-3} Kg)	Y_O	Y_F	T_U		P_{max}	$m^{t=ti}$	$m^{t=to}$	
Downside slot opening	Exp	-		12.7	10.42	388	-	1.71	0.011	0.164	yes
	Sim			12.3	9.10	425	9.75	2.13	0.013	0.12	yes
	Exp	20-30	40.4	14.16	8.79	386	-	0.80	0.015	0.013	no
	Sim					400		1	0.018	-	no
Door Opening	Exp	-		11.6	9.31	375	-	2.28	0.018	0.094	yes
	Sim			12.5	8.29	415	6.07	2.30	0.017	0.093	yes
	Exp	30-40	34	14.2	9.11	371	-	2.02	0.010	0.092	yes
	Sim			12.58	8.08	423	6.05	1.7	0.014	0.103	yes
Window Opening	Exp	-		12.5	9.33	372	-	27.18	0.025	0.165	no
	Sim			12.5	8.29	415	18.84	31.89	0.02	0.153	no

As expected, in the window case, the predicted maximum pressure (P_{MAX}) was the highest as shown in Fig. 1 and Table 1. This is thought to be due to the relative small opening area of the window restricting the flow coming out. The predicted pressures for all cases are generally in reasonable agreement with the measurements. It is interesting to note the relatively low pressures in all the cases. This is thought to be partly due to the considerable dilution in the container which led to decreases in the corresponding laminar burning velocity. Also, thee relatively large opening area allowed the flame to propagate out almost without restriction, except for the window case which had the highest pressure.

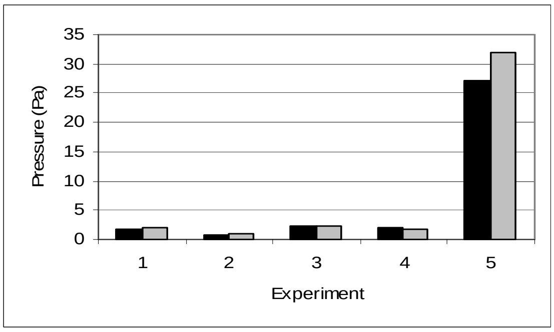

Fig. 1 Experiment (black) and simulated (grey) values of the P_{MAX}.

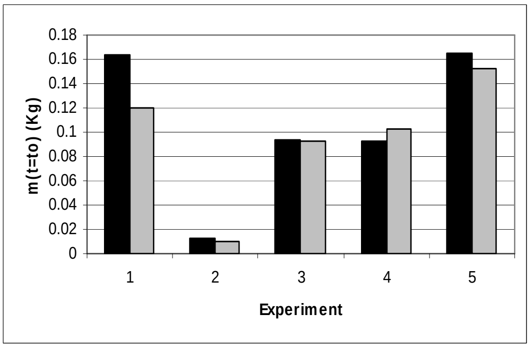

Fig. 2 Experiment (black) and simulated (grey) values of the total mass inflow ($m^{t=to}$)

In Fig.2 and also Table 1, comparison is made between the measured and predicted on the total mass outflow at the moment when the deflagration reaches the opening ($m^{t=t0}$). The predictions follow the same trend as the experiments.

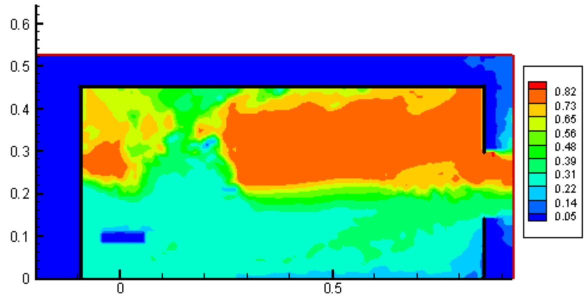

Fig. 3 Diluent mass fraction (Y_D) 0.4 s after ignition for the window case.

Figure 3 shows the outflow of hot gases through the opening. In line with experimental observations, relatively large degree of dilution was predicted in the upper layer, rendering the mixture there to be close to the lower flammable limit (LFL). Detailed analysis of the results revealed that the injection of the watermist lead to an overall decrease in flame speed, leaving some region out of the flammable range and others in.

From the last column in Table 1, it can be seen that in tests 1 and 2, the presence of water vapour suppressed the fire ball. On the contrary, for the door case, tests 3 and 4, deflagration outside the container was observed with or without watermist. In the window case, there was no fire ball even when there was no watermist. These events do not correlate with the average fuel concentration (Y_F), either experimental or predicted, in the upper layer as shown in Table 1, implying that the occurrence of the fire ball outside the container does not only depend on the averaged value of the fuel concentration in the upper layer. In the window case, the one with the largest amount of flammable mixture, the opening area was too small and the expanding gas at the back forced the non-flammable gases in the upper layer to move downwards at the open end and break the flammable surface. Without this flammable surface, the flame could not propagate through the window. In the other cases, the opening area was large enough to allow the burnt gases to flow out through the upper section of the opening, leaving the flammable surface in lower layer to propagate smoothly through the lower part of the opening.

In conclusion, it has been found that (1) the presence of diluent effectively reduces the likelihood of fire ball outside the container by decreasing or cancelling the laminar burning velocity; (2) the ignition time is directly affected by the end opening area. Openings with an area extended from the floor to the ceiling are more likely to produce high velocity gravity currents and therefore shorter ignition times while producing, at the same time, both large mixing and flammable volume; (3) small opening areas, located far from the floor, reduce the inflow mass and delay the ignition time and, possibly, the fire ball outside of the container by means of cutting the flammable surface through the opening and (4) The occurrence of the fire ball outside the container does not correlate with the averaged value of the fuel in the upper layer.

References

[1] W. Weng and W. Fan. Experimental study on the mitigation of backdraft in compartment fires with water mist. Journal of Fire Sciences 2002; 20: 259-277.

[2] K. McGrattan and G. Forney, Fire Dynamics Simulator (Version 4). Technical Reference Guide. 2004, National Institute of Standards and Technology.

[3] P. Domingo, L. Vervisch and J. Réveillon. DNS Analysis of Partially Combustion in Spray and Gaseous Turbulent Flame-Bases Stabilized in Hot Air. Combustion and Flame 2005; 140: 172-195.

[4] Domingo, P., Vervisch, L. and Bray, K., Partially Premixed Flamelets in LES of Non-Premixed Turbulent Combustion. Combust. Theory Modelling, 2002. **6** (2002) p. 529-551.

[5] H. Pitsch, FlameMaster Code, 1996.