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Abstract

In large-scale mass fires generated in forests or by a nuclear event, the area of the fire is large (diameter 1 or more kilometers) whereas the flame height is relatively small (less than 10 meters) creating a large turbulent buoyant plume. This paper determines a correlation for the magnitude of velocity such a flow generates near above the ground at the edges of the mass fire. This induced wind velocity is due primarily to the total cumulative buoyant plume above the mass fire. Therefore, this situation can be simulated by using a pure buoyant plume (for example of helium) representing the buoyant flow above the flame height and having a diameter representing that of the mass fire. A similarity and numerical study of turbulent buoyant helium plumes is presented to determine and correlate the induced velocity near the ground in terms of the total buoyancy or equivalent heat release rate and the diameter of the source fire. The similarity analysis is based on relations for large buoyant plumes which have also been recently supported by experiments. Simulations for validation using the fire dynamics simulator (FDS) were performed for literature data for a 1 m helium plume source.

Keywords	: Large area fires;turbulent plumes; computational fluid dynamics; fire dynamics simulator

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Suggested reviewers	Longhua Hu, Jennifer Wen, Bart Merci

Submission Files Included in this PDF

File Name [File Type]

Letter to the editor. OCTOBER 2019.docx [Cover Letter]

RESPONSE to reviewers October 11.docx [Response to Reviewers]

FINAL BLACK revised October 2019.docx [Manuscript File]

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Letter to the editor , October 9, 2019

Paper : Ground Wind Generated Near the Base by the massive convective column of Very Large-Scale Mass Fire

Prof. Bart Merci

Dear Professor Merci

Thank you for the suggestions n resubmitting the paper.

Please find the revised paper and read the detailed response to the comments of reviewer 3.

I find the following excerpt from this review puzzling.

"In the end, I do not recognize the scaling rules applied to the velocity. In the paper by Baum and McCaffrey (2nd IAFSS), an analysis is done to estimate the fire induced wind field resulting from a mega-fire spread over kilometers. They use D*=(Q/rho cp T sqrt(g))^0.4 as the length scale, and sqrt(gD*) as the velocity scale. I think that something similar is being done in the current paper, but I cannot follow the flow. This reminds me of many experiences I have had over the years reading these "classic" plume analyses. It all looks similar, but each person has a slightly different take, which is not necessarily better or worse than the others."

I have revised the response to reviewer 3 about the structure of the paper as follwows :

1. The major comment according about the structure of the paper. First, the structure of the paper is good, having first the proposed correlations, then verification of the FDS code *as we have used it*, and then the numerical results of this code for validation of correlation and determination of the parameters. **IT IS IMPORTANT TO NOTICE THAT THE SECTION FOR VERIFICATION OF THE CODE WITH THE HELIUM DATA TAKES ONLY ONE PAGE out of 16 paper pages**. The correlations are derived carefully for this case of mass fires with the proper *general* background for buoyant flows in Ref [1] which the fundamental physics are presented. No change in the structure is needed as also the other two reviewers agree with.

   We reproduce here the description and logic of the structure from the paper which is reasonable:

   "The paper is organized in the following way. We first use similarity analysis to make a prediction for the mass entrainment and the related wind generated by the massive thermal plume. Next, we numerically simulate using Fire Dynamics Simulator (FDS) [8] the thermal plume and the wind induced near its base by using helium release as a buoyancy source, where these calculations are validated by experiments using helium

available in the literature for a source diameter 1m [9]. Subsequently, predictions are made for various plume source sizes and flow rates. Based on the results from all simulations with 3D circular sources, the maximum horizontal velocity is correlated with the fire source diameter and the equivalent heat release rate determined from the buoyancy of the helium flow. Finally, simulations are performed for a 2D case mass fire case, simulating a forest line front, where the source length is set in that direction the same as the computational domain while the fire source width varies."

The following comments try to explain how this analysis is related to Baum and McCaffrey paper.

Looking forward to your decision.

Sincerely

Michael Delichatsos

RESPONSE to reviewers October 11, 2019

We thank all reviewers

Reviewer 1. Thank you for the suggestion.
I think that it was clear why this work is important but anyway we have added this sentence at the beginning of the introduction.

"*In large-scale mass fires generated in forests or by a nuclear event, the area of the fire is large (diameter 1 or more kilometers) whereas the flame height is relatively small (less than 10 meters) creating a large turbulent buoyant plume. This paper determines a correlation for the magnitude of velocity such a flow generates near above the ground at the edges of the mass fire. This phenomenon is significant because the induced wind will cause sustained flame spread and growth of the fire in adjacent built environment*."

In addition we have highlighted again that the dynamics are the same for any scale as long as the flow is turbulent.

Reviewer 2.

Thank you much for the kind words.

Reviewer 3 RESPONSE (THEIR COMMENTS ARE AT THE END OF THIS DOCUMENT)
Thank you, this reviewer, too.
The reviewer makes some good points, but we think that the reviewer is not focusing and addressing our physical problem disagreeing with his comments. We also think that no change of the structure of the paper is necessary. We respond to each relevant point of the reviewer next.

1. The major comment according about the structure of the paper. First, the structure of the paper is good, having first the proposed correlations, then verification of the FDS code *as we have used it*, and then the numerical results of this code for validation of correlation and determination of the parameters. IT IS IMPORTANT TO NOTICE THAT THE SECTION FOR VERIFICATION OF THE CODE WITH THE HELIUM DATA TAKES ONLY ONE PAGE out of 16 paper pages. The correlations are derived carefully for this case of mass fires with the proper *general* background for buoyant flows in Ref [1] which the fundamental physics are presented. No change in the structure is needed as also the other two reviewers agree with.

   We reproduce here the description and logic of the structure from the paper which is reasonable:

   "The paper is organized in the following way. We first use similarity analysis to make a prediction for the mass entrainment and the related wind generated by the massive thermal plume. Next, we numerically simulate using Fire Dynamics Simulator (FDS) [8] the thermal plume and the wind induced near its base by using helium release as a

buoyancy source, where these calculations are validated by experiments using helium available in the literature for a source diameter 1m [9]. Subsequently, predictions are made for various plume source sizes and flow rates. Based on the results from all simulations with 3D circular sources, the maximum horizontal velocity is correlated with the fire source diameter and the equivalent heat release rate determined from the buoyancy of the helium flow. Finally, simulations are performed for a 2D case mass fire case, simulating a forest line front, where the source length is set in that direction the same as the computational domain while the fire source width varies."

The following comments try to explain how this analysis is related to Baum and McCaffrey paper.

2. Second, it is fortunate that we had considered the mentioned paper by Baum and McCaffrey after studying it in detail. Therefore, we are prepared to say that we had found that this paper, beside the math of Baum, does not have the correct physics. In this paper, Gaussian profiles for the velocities and temperature in the fire plume are assumed and used to calculate the source vorticity and expansion needed for the calculation of the induced potential flow. But the temperature profile is not Gaussian: it is the mixture fraction that it is Gaussian from which the temperature can be calculated through a pdf. And also, the effects of the diameter are not included in these distribution profiles. Therefore, the physics, *the scaling* and the details of the flow inside the plume are not right for large area fire sources.

3. Third, the application for a large fire as being the contribution of individual small fires (at the end of the paper Baum and McCaffrey) is inadequate by not taking into account the merging of the fire plumes and the effects of fire area size, phenomena very important for the present situation.

4. Fourth, we think that ref [1] would also be useful to understand the scaling and physics not simply as correlations.

APPENDIX

REVIEWER 3 COMMENTS for reference to response

The paper describes the derivation of a simple model that estimates ground level wind speed induced by a very large fire. This was a topic of great interest back in the 1980s when the concept of "nuclear winter" was a subject of research. The main problem I have with this paper is that it is very disorganized, correlations appear with no explanation, the CFD analysis seems completely detached from the flow of the paper, figures, notation and equations are sloppy. In the end, I do not recognize the scaling rules applied to the velocity. In the paper by Baum and McCaffrey (2nd IAFSS), an analysis is done to estimate the fire induced wind field resulting from a mega-fire spread over kilometers. They use D*=(Q/rho cp T sqrt(g))^0.4 as the length scale, and sqrt(gD*) as the velocity scale. I think that something similar is being done in the current paper, but I cannot follow the flow. This reminds me of many experiences I have had over the years reading these "classic" plume analyses. It all looks similar, but each person has a slightly different take, which is not necessarily better or worse than the others. With this in mind, I would like to see a much shortened version of the paper that uses as much as possible the scalings and correlations that are still in use today. For example, how does this analysis differ from Baum and McCaffrey? Maybe it's the same, but I cannot follow the algebra. The shortened paper need not dwell on the validation of FDS --- the 1 m helium plume calculation is included in the FDS Validation Guide. Just cite it and move on. FDS should only play the role of calculating the inevitable constant for the final correlation. Don't make it the focus of the paper---it just confuses things more.

Ground Wind Generated Near the Base by the massive convective column of Very Large-Scale Mass Fires

By

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Abstract

In large-scale mass fires generated in forests or by a nuclear event, the area of the fire is large (diameter 1 or more kilometers) whereas the flame height is relatively small (less than 10 meters) creating a large turbulent buoyant plume. This paper determines a correlation for the magnitude of velocity such a flow generates near above the ground at the edges of the mass fire. This induced wind velocity is due primarily to the total cumulative buoyant plume above the mass fire. Therefore, this situation can be simulated by using a pure buoyant plume (for example of helium) representing the buoyant flow above the flame height and having a diameter representing that of the mass fire. A similarity and numerical study of turbulent buoyant helium plumes is presented to determine and correlate the induced velocity near the ground in terms of the total buoyancy or equivalent heat release rate and the diameter of the source fire. The similarity analysis is based on relations for large buoyant plumes which have also been recently supported by experiments. Simulations for validation using the fire dynamics simulator (FDS) were performed for literature data for a 1 m helium plume source. Subsequently, simulations were carried out for various source sizes and for a range of helium flow rates to deduce a correlation between the maximum horizontal velocity with the buoyancy rate and the fire plume diameter. Finally, additional simulations were performed for a 2D case where the fire source length was set the same as the computational domain in that direction

with varying fire source widths and flow rates and it is found that similar relation as that deduced for a 3D plume also applies to the 2D case with the characteristic length being the length of the fire source. In this work, we do not address asymmetric fire source load conditions, which may or may not generate fire whirls.

Keywords: Large area fires, turbulent plumes, computational fluid dynamics, fire dynamics simulator

1. Introduction

In large-scale mass fires generated in forests or by a nuclear event, the area of the fire is large (diameter 1 or more kilometers) whereas the flame height is relatively small (less than 10 meters) creating a large turbulent buoyant plume. This paper determines a correlation for the magnitude of velocity such a flow generates near above the ground at the edges of the mass fire. This phenomenon is significant because the induced wind will cause sustained flame spread and growth of the fire in adjacent built environment. In these large-scale mass fires (such as a large conflagration following a nuclear explosion), the area of the fire is very large (diameter 1 or more kilometers) and the flame height is much smaller, creating above the fire a large turbulent buoyant plume. The flame height of large area fires is controlled by the heat release rate per unit area and is given by the following relation [1]:

$$\frac{H_f}{D} = 18.8\left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} D^{\frac{5}{2}}}\right)^2 = 18.8\left(\dot{Q}_D^*\right)^2 \qquad \text{if} \qquad \dot{Q}_D^* < 0.23 \tag{1a}$$

where H_f is the flame height (m), D the diameter of the fire (m), $\dot{Q}$ the heat release rate (kW), ρ_∞ is the density of ambient air (kg/m^3), c_p the specific heat capacity of ambient air (kJ/kg-K), T_∞ the ambient air temperature (K), g the gravitational constant (9.81 m/s^2).

Substituting the constant values of air properties in Eq. (1a), we have

$$H_f = 9.2 \times 10^{-6} \left(\dot{Q}''\right)^2 \tag{1b}$$

where $\dot{Q}''$ is the heat release rate per unit area (kW/m^2). Equation (1b) implies that the flame height of a mass fire is independent of diameter.

The condition for applicability of Eq. (1a) is easily satisfied for large area fires (D>500m) produced by heat release rate per unit area 500-1000 kW/m^2, which is common in domestic or forest fires. The flame height would be less than 10 m (above the base of the fire) regardless of the fire size if the heat release rate is 1000 kW/m^2.

The buoyant plume above the mass fire will generate a horizontal velocity near the ground which is the main objective of this work to determine. There is evidence [1,2,3] that the mass fire will consist of local fires of the size of the length scale determined by Eq. (1b). We expect that the ground wind generated by the cumulative massive thermal plume is much greater than the winds generated by the local fires at their base. Therefore, this situation can be simulated by using a pure buoyant plume representing the buoyant flow above the flame height and having a diameter representing that of the mass fire. We note that the dynamics and similarity of this flow will be the same for any size turbulent buoyant plume.

There have been a number of studies on the flow dynamics of large-scale buoyant plumes [e.g., 4-6]. It has been observed that the flow contracts as it moves away from the source reaching a minimum radius, or neck, beyond which the plume begins to expand eventually forming a pure plume with the radius growing linearly with height and that the height of the neck is approximately equal to one source radius and the neck has a radius of approximately half the source radius. The air entrainment into a large-scale thermal plume, which is critically important in understanding the flow dynamics of the thermal plume, was however not measured in these studies. In a more recent study [7], the volume flux of a buoyant turbulent plume emerging from a large area source with low initial momentum flux was measured and it was found that the volume flux in the plume increases linearly from the source to the neck, which is consistent with the finding in [1].

The objective of this study is to examine the mass entrainment and the related wind generated by the massive thermal plume based on similarity analysis and computational fluid dynamic (CFD) modelling. It is worth noting that this similarity and numerical analysis for the mass entrainment has been recently validated [7] experimentally providing a further incentive to validate the correlation for the wind generated near the ground.

The paper is organized in the following way. We first use similarity analysis to make a prediction for the mass entrainment and the related wind generated by the massive thermal plume. Next, we numerically simulate using Fire Dynamics Simulator (FDS) [8] the thermal plume and the wind induced near its base by using helium release as a buoyancy source, where these calculations are validated by experiments using helium available in the literature for a source diameter 1m [9]. Subsequently, predictions are made for various plume source sizes and flow rates. Based on the results from all simulations with 3D circular sources, the maximum horizontal velocity is correlated with the fire source diameter and the equivalent heat release rate determined from the buoyancy of the helium flow. Finally, simulations are performed for a 2D case mass fire case, simulating a forest line front, where the source length is set in that direction the same as the computational domain while the fire source width varies.

2. SIMILARITY ANALYSIS

We remind the reader that fires [1] can be conveniently distinguished in three types as Fig. 1 illustrates: buoyant jets, pool fires and mass fires, where the distinction is based roughly on the fire Froude number defined as follows:

$$Fr_f = \frac{\dot{Q}g}{\rho_\infty c_p T_\infty D^{\frac{5}{2}} \left(\frac{\Delta T_f}{T_\infty} g\right)^{3/2}} \tag{2a}$$

Here ΔT_f is the mean temperature rise over the ambient as affected by radiation losses, efficiency and fluctuations. It is usually nearly constant (800 K) for hydrocarbon-based materials.

The heat release rate is taken here to be equal to the convective heat release rate which is related to the buoyancy flux (for example for Helium release) by the following relation

$$B = \frac{\dot{Q}g}{c_p T_\infty} \tag{2b}$$

Our focus here is the mass fires as shown in the bottom part of Fig. 1, which exist for $Fr_f < 0.01$. The flow generated in this situation is illustrated in Fig. 2. The flame height in this case is given by Eq. (1) being less than 10m independent of the source diameter as discussed following Eq. (1) so that the massive cumulative convective flow above the fire, as illustrated in Fig. 2 , is the main cause of the wind induced by the fire near its base. Our next task is to derive an expression for this wind speed near the base of the fire plume.

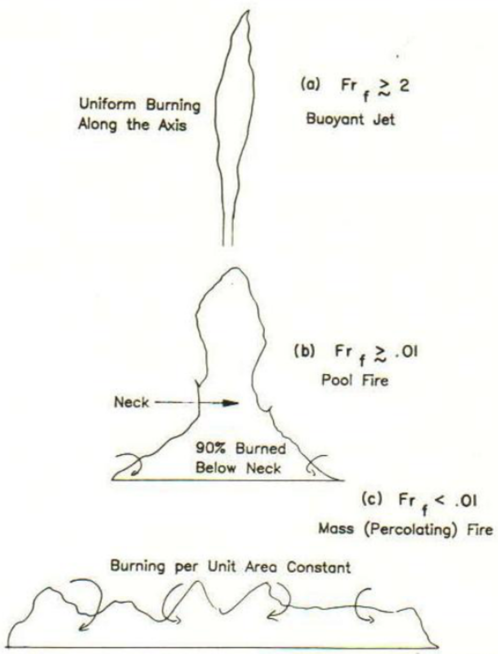

Figure 1. Three characteristic types of turbulent flames: buoyant jet, poof fire and mass fire delineated by their fire Froude number (Eq. (2a)).

The flow of the large convective fire plume consists of three regimes, one near its base, one in the necking area and one in the asymptotic regime, as shown in Fig. 2. The fire convective flow is conserved according to the following relation based on similarity of the flow:

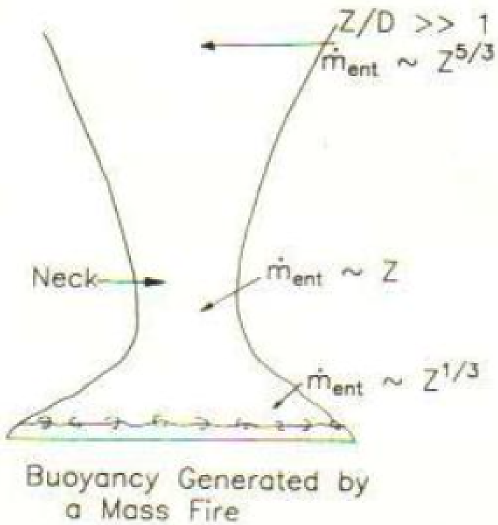

Figure 2. Illustration of different entrainment regimes for mass fires

$$\dot{m}_{ent}(Z)c_p\Delta T_c \sim \dot{Q} \tag{3a}$$

Here $\dot{m}_{ent}$ is the entrainment rate to a height Z and ΔT_c is the centreline excess temperature. The symbol ~ denotes that the sides of equation are proportionally related by a pure number.

The entrainment velocity at a height Z and the average entrainment velocity up to a height Z in buoyant flows are both given by :

$$U_{ent}(Z) \sim \sqrt{\frac{\Delta T_c}{T_\infty} gZ} \tag{3b}$$

but having different proportionality coefficients,

The mass entrainment rate up to a height Z is given by:

$$\dot{m}_{ent}(Z) \sim \rho_\infty U_{ent}(Z) A_e \tag{3c}$$

where the entrainment area A_e can be expressed by the following relations in the three regions of the massive plume:

$$A_e \sim \begin{cases} D^2 & \text{in the base region} \\ DZ & \text{in the necking region} \\ Z^2 & \text{in the asymptotic region} \end{cases} \tag{4}$$

By combining Eqs. (2) to (4) we can obtain the entrainment rate, the temperature rise and the velocity in the three regimes. We present here the entrainment and the velocity in the lower two regimes because these relations in the asymptotic regime are well known.

<u>Entrainment rate and centreline velocity near the base</u>

$$\frac{\dot{m}_{ent}}{\rho_\infty \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty}\right)^{1/3} D^{5/3}} \sim \left(\frac{Z}{D}\right)^{1/3} \quad \text{and} \quad U_{ent} \sim \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \left(\frac{Z}{D}\right)^{1/3} \tag{5a}$$

<u>Entrainment rate and centreline velocity near the necking area</u>

$$\frac{\dot{m}_{ent}}{\rho_\infty(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty})^{1/3} D^{5/3}} \sim \frac{Z}{D} \quad \text{and} \quad U_{ent} \sim \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \sim U_{wind} \qquad (5b)$$

Note that velocity in the necking area, Eq. (5b), is independent of height Z. It is also important to note that the entrainment rate correlation in Eq.(5b) has been validated by recent experiments in [7].

Based on the present analysis the wind induced velocity will be given by the second relation in Eq. (5b), which is the proposition to validate and find the proportionality coefficient in this work.

We proceed next with the development of the numerical simulation used to calculate the induced velocity near the ground. As we stated earlier, we do the calculations for a helium produced buoyant flow which scales the mass fire produced buoyancy in smaller size.

3. Numerical Details

Fire Dynamics Simulator (FDS, version 6) [8] was used for the present simulations with the dynamic Smagorinsky model for turbulence. Simulations were carried out for three 3D circular plumes 0.5, 0.8 and 1m in diameter and a 2D plume. The width, length and height of the computational domain vary for different cases but they were chosen in such a way that they have minimum effect on the simulation results. The circular source was approximated with small square sources. The total number of computational control volumes also varies for different cases, ranging from 4.5 million to 8 million. Grid sensitivity studies were carried out for each case showing further refinement of the grid size has negligible influence on the results. The total simulation time was 20s for all cases that is sufficient for the flow to reach the steady state and the results presented in this paper are those averaged between 10 and 20 s.

4. Results and Discussions

4.1. Validation of the numerical simulation by comparison with experimental data in [9]

Figure 3 presents a comparison of the 2D contour of the experimental data in [9] and predicted helium mass fraction. Generally, the predictions are in good agreement with the measurements. FDS predicts reasonably well the helium mass fraction at lower heights, i.e., within 40cm above the source, whereas it overpredicts the helium mass fraction at higher locations. The predicted prolonged helium profile can be explained by examining the prediction of the axial velocity as shown in Fig. 4. The maximum predicted axial velocity is 4 m/s occurring at 1m above the source compared to 3 m/s observed in the experiment at 0.7 m above the source.

Experiment

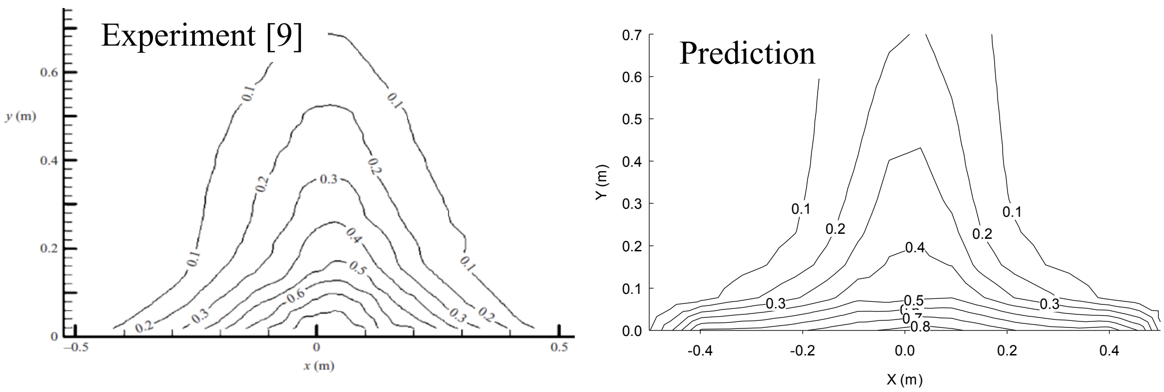

Figure 3. Comparison of experimental [9] and predicted helium mass fraction for a circular plume source with a diameter of 1m.

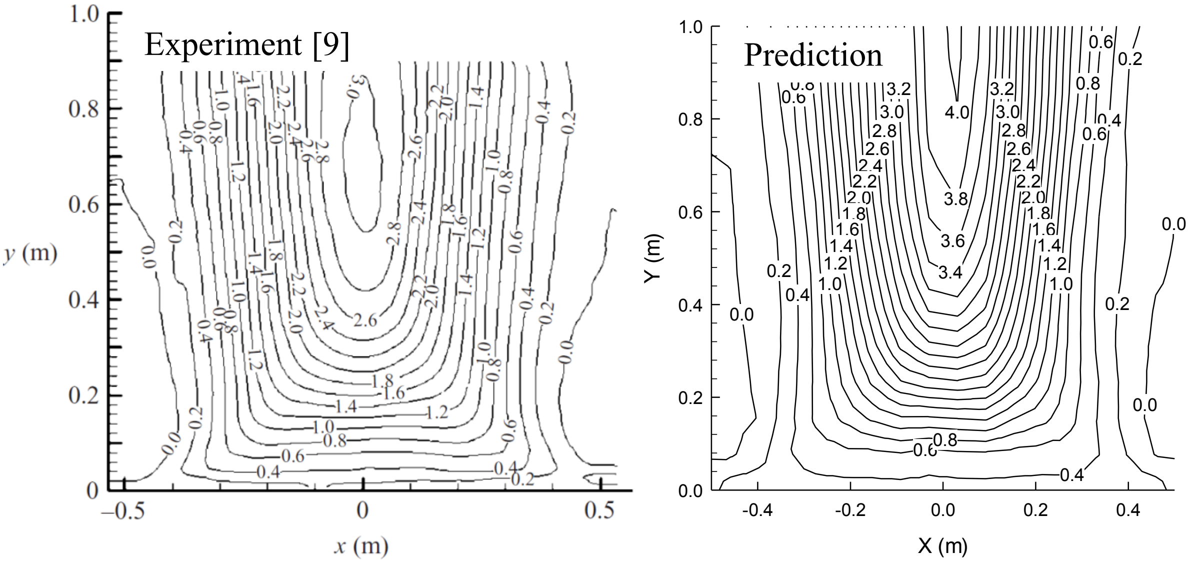

Figure 4. Comparison of experimental [9] and predicted vertical velocity for a circular plume source with a diameter of 1m.

Figure 5 shows the results for the horizontal velocity. The prediction is similar to the measurements except for a slight over-prediction of the maximum horizontal velocity, about 0.9 m/s compare to 0.7 m/s observed in the experiment. The maximum horizontal velocity occurs near the plume source and about 0.25 m from the center of the plume (i.e., half of the radius of the plume source) as reported in [4-6].

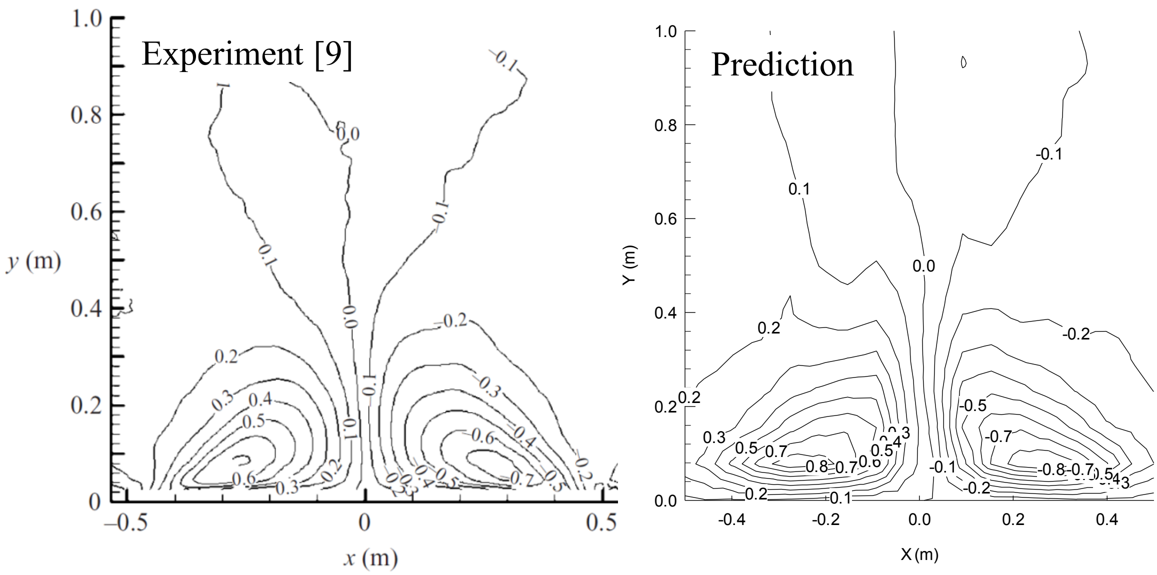

Figure 5. Comparison of experimental [9] and predicted horizontal velocity for a circular plume source with a diameter of 1m.

4.1. Maximum horizontal velocity in 3D mass fires

This section includes results for a 3D axisymmetric mass fire plume whereas the next section includes results for a 2D mass line fire.

Having established confidence in the computational simulation, we proceed next to calculate the maximum horizontal velocity induced by the helium buoyant flow. The relation of the helium flow rate to the corresponding heat release rate is given by

$$\dot{V}_{He} = \frac{1000\dot{Q}}{\rho_\infty c_p(\rho_\infty - \rho_{He})} \approx 3.3\dot{Q} \tag{6}$$

where $\dot{V}_{He}$ is the volume flow rate of helium in liter/s, and $\dot{Q}$ is the heat release rate in kW.

The maximum induced horizontal velocity is determined as the average of absolute values of the maximum horizontal velocity from diametric opposite (upstream and downstream) sides near the base of the plume. We use the prediction of Eq. (5b) to correlate these numerical results dropping for convenience the value for the ambient properties and the gravitational acceleration

$$\frac{g}{\rho_\infty c_p T_\infty} = 0.027\ m^4/s^2/kJ \tag{7a}$$

Therefore, we plot the maximum induced velocities in Fig. 6 versus a reduced heat release rate parameter $(\dot{Q}/D)^{1/3}$ for all the simulations carried out in this study (i.e., different source diameters and HRRs). The result verifies our similarity analysis as all the data collapsed onto a single line having the following correlation:

$$U_{max} = 0.22(\dot{Q}/D)^{1/3} = 0.73\left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \tag{7b}$$

Here velocities are in m/s, heat release rates in kW and diameters in m.

This result is significant because it provides a direct means to estimate the induced velocity from a turbulent plume if the heat release rate (or the flow rate for an inert plume) and dimensions of the source are known.

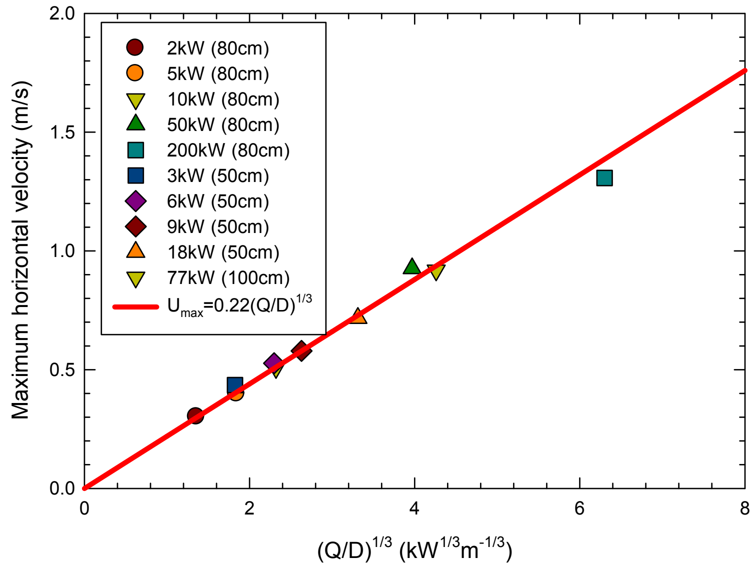

Figure 6. Maximum horizontal velocity plotted against the reduced normalized heat release rate, $\left(\dot{Q}/D\right)^{1/3}$, where D is the diameter of the source.

4.2 Maximum horizontal velocity in 2D mass line fires

In this section we extend the numerical calculation for a simulation of 2D mass fire merged buoyant flow which develops when the width of the line fire is large, for example more than 500m. In the analysis we vary the width and keep the length of the line fire constant at L= 2 m. We designate the length L as D in the correlations.

4.2.1. Vertical velocity for validation

For a 2D plume, the simulations are still three dimensional, but the length of the plume source was set as the same as the computational domain in that direction (2m) whereas the width of the plume source and the flow rate were varied. Simulation results at different cross sections verify that the flow is essentially two dimensional. Figure 7 shows the vertical velocity at different initial helium velocities/HRRs for the case with the width of the source equal to 0.4 m. The flow accelerates quickly after its release before reaching its maximum value. It is known that for a 2D plume the vertical velocity does not decrease after reaching its maximum as verified in Fig. 7.

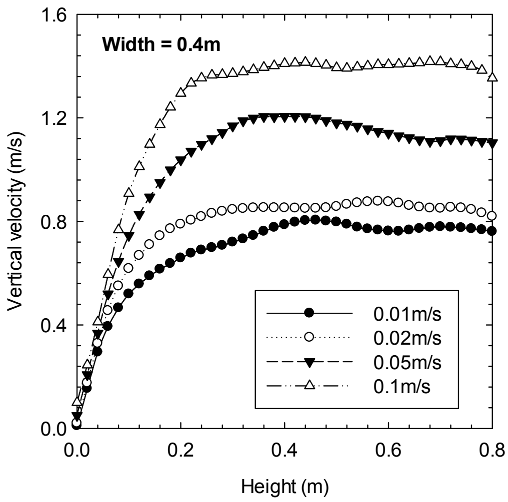

Figure 7. Vertical velocity at different initial helium velocities/HRRs for the 2D plume with a source width equal to 0.4 m.

Figure 8 plots the maximum vertical velocity for all cases (four widths of the plume source × four heat release rates as a function of $(\dot{Q}/D)^{1/3}$, where D is the length of source (2 m for all cases) and the result indicates that for a 2D turbulent plume the following relation exists:

$$V_{max} = 0.65(\dot{Q}/D)^{1/3} = 2.16\left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \quad (8)$$

This value of the coefficient in Eq. (8) is in good agreement with the corresponding coefficient (0.62) measured in the far field of line fire plumes in [10].

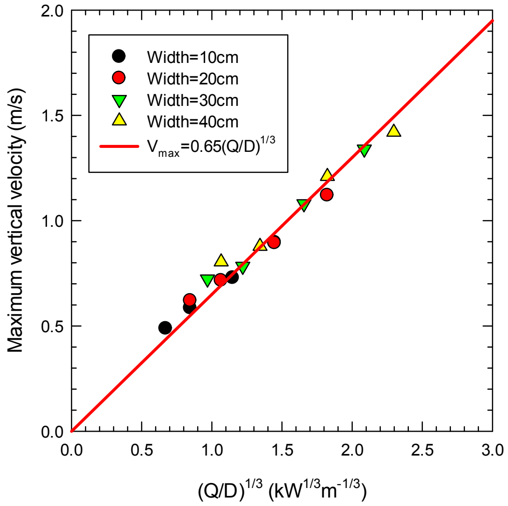

Figure 8. Maximum vertical velocity from a 2D plume plotted against the reduced normalized heat release rate, $(\dot{Q}/D)^{1/3}$, where D is the length of source (2 m for all cases).

4.2.2. Maximum Horizontal induced velocity in 2D mass fires

The maximum induced horizontal velocity is determined similarly as for the 3D plumes, i.e., the average of absolute values of the maximum horizontal velocity from opposite (upstream and downstream) sides near the base of the plume. The maximum horizontal velocity for the 2D plume is plotted in Fig. 9, where we note that the same correlation as found in the 3D plume applies to the 2D case as well, namely $U_{max} = 0.22(\dot{Q}/L)^{1/3} = 0.73\left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty L}\right)^{\frac{1}{3}}$, with the characteristic length being the length of the plume source for the 2D plume as opposed to the diameter of the source for the 3D plume. There is some scattering for the case with the width of the source equal to 10 cm probably because the flow is not fully turbulent when the width of the source is small.

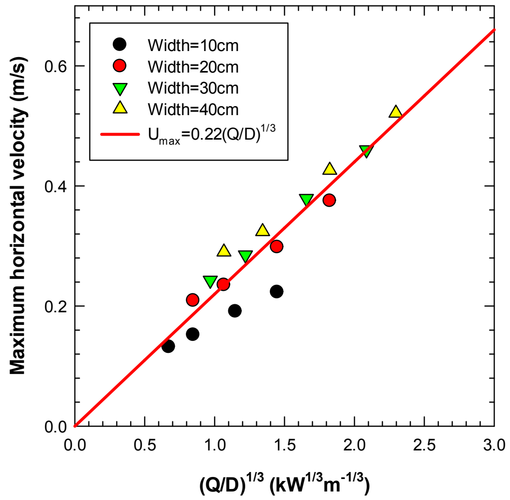

Fig. 9. Maximum horizontal velocity from the 2D mass fire plumes for various widths plotted against the reduced normalized heat release rate, $\left(\dot{Q}/D\right)^{1/3}$, where D is the length of source L.

5. Concluding remarks

This work investigates the induced velocity near the ground in large-scale mass fires such as a deflagration following a nuclear explosion. This situation can be simulated using a buoyant plume of helium representing the buoyant flow above the flame height (less than 10m) of the large area fire deflagration (greater than 500m), see Eq. 1. A similarity and numerical study of turbulent helium buoyant plumes was presented. Fire Dynamics Simulator (FDS) was firstly validated against literature data and then used to deduce the correlation between the maximum horizontal velocity with the heat release rate (helium flow rate) and the fire source diameter. The key findings of this work are:

- A similarity correlation was developed for the entrainment and the velocity in a mass fire produced plume, Eqs. (5a) and (5b). The similarity for the entrainment has been recently validated experimentally [7]. Our solution allows us to predict that the wind induced velocity is given by $U_{ent} \sim \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \sim U_{wind}$.

- FDS is capable of predicting well the flow induced in non-reactive turbulent buoyant plumes [9] near the base (Figs. 2-4), but it overpredicts the vertical velocity to some extent resulting in a prolonged helium profile compared to experimental data.
- For both 2D and 3D plumes, the maximum horizontal velocity can be correlated to the heat release rate $\dot{Q}$ and a characteristic length, D, by $U_{max} = 0.22(\dot{Q}/D)^{1/3} = 0.73 \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}}$, where D is the source diameter for the 3D case and the length of the source for the 2D case (Figs. 6 and 9). As an example, we note that for large conflagration 1000 m in diameter having a heat release rate of 800kW/m^2, the induced velocity near the ground would be 18.83 m/s or 67.8 km/h (the flame height would be 5.9 m, see Eq. 1). These results can be applied in case of a nuclear deflagration, a case for which this work was funded for.
- The FDS prediction is further validated by verifying that the vertical velocity in a 2D simulated mass fire plumes does not decrease with height after reaching its maximum value (Fig.7) which agrees with experiments. Specifically, the following correlation exists for the vertical centerline velocity $V_{max} = 0.65(\dot{Q}/D)^{1/3} = 2.16 \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}}$, where velocity is in m/s, heat release rate in kW and length in m and D is the length of the mass fire line plume.

Further work is anticipated to examine the effects on very large area fires of various imposed atmospheric winds including the possible generation of fire whirls.

Acknowledgements

This project was financially supported by Atomic Weapon Establishment, UK.

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Conflict of interest

No Conflict exists.

Michael Delichatsios

Ground Wind Generated Near the Base by the massive convective column of Very Large-Scale Mass Fires

By

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Abstract

In large-scale mass fires generated in forests or by a nuclear event, the area of the fire is large (diameter 1 or more kilometers) whereas the flame height is relatively small (less than 10 meters) creating a large turbulent buoyant plume. This paper determines a correlation for the magnitude of velocity such a flow generates near above the ground at the edges of the mass fire. This induced wind velocity is due primarily to the total cumulative buoyant plume above the mass fire. Therefore, this situation can be simulated by using a pure buoyant plume (for example of helium) representing the buoyant flow above the flame height and having a diameter representing that of the mass fire. A similarity and numerical study of turbulent buoyant helium plumes is presented to determine and correlate the induced velocity near the ground in terms of the total buoyancy or equivalent heat release rate and the diameter of the source fire. The similarity analysis is based on relations for large buoyant plumes which have also been recently supported by experiments. Simulations for validation using the fire dynamics simulator (FDS) were performed for literature data for a 1 m helium plume source. Subsequently, simulations were carried out for various source sizes and for a range of helium flow rates to deduce a correlation between the maximum horizontal velocity with the buoyancy rate and the fire plume diameter. Finally, additional simulations were performed for a 2D case where the fire source length was set the same as the computational domain in that direction

Commented [1]: Rev 1

with varying fire source widths and flow rates and it is found that similar relation as that deduced for a 3D plume also applies to the 2D case with the characteristic length being the length of the fire source. In this work, we do not address asymmetric fire source load conditions, which may or may not generate fire whirls.

Keywords: Large area fires, turbulent plumes, computational fluid dynamics, fire dynamics simulator

1. Introduction

In large-scale mass fires generated in forests or by a nuclear event, the area of the fire is large (diameter 1 or more kilometers) whereas the flame height is relatively small (less than 10 meters) creating a large turbulent buoyant plume. This paper determines a correlation for the magnitude of velocity such a flow generates near above the ground at the edges of the mass fire. This phenomenon is significant because the induced wind will cause sustained flame spread and growth of the fire in adjacent built environment. In these large-scale mass fires (such as a large conflagration following a nuclear explosion), the area of the fire is very large (diameter 1 or more kilometers) and the flame height is much smaller, creating above the fire a large turbulent buoyant plume. The flame height of large area fires is controlled by the heat release rate per unit area and is given by the following relation [1]:

Commented [2]: Rev 2

$$\frac{H_f}{D} = 18.8\left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} D^{\frac{5}{2}}}\right)^2 = 18.8\left(\dot{Q}_D^*\right)^2 \qquad \text{if} \qquad \dot{Q}_D^* < 0.23 \qquad (1a)$$

where H_f is the flame height (m), D the diameter of the fire (m), $\dot{Q}$ the heat release rate (kW), ρ_∞ is the density of ambient air (kg/m^3), c_p the specific heat capacity of ambient air (kJ/kg-K), T_∞ the ambient air temperature (K), g the gravitational constant (9.81 m/s^2).

Substituting the constant values of air properties in Eq. (1a), we have

$$H_f = 9.2 \times 10^{-6} (\dot{Q}^{"})^2 \quad (1b)$$

where $\dot{Q}^{"}$ is the heat release rate per unit area (kW/m^2). Equation (1b) implies that the flame height of a mass fire is independent of diameter.

The condition for applicability of Eq. (1a) is easily satisfied for large area fires (D>500m) produced by heat release rate per unit area 500-1000 kW/m^2, which is common in domestic or forest fires. The flame height would be less than 10 m (above the base of the fire) regardless of the fire size if the heat release rate is 1000 kW/m^2.

The buoyant plume above the mass fire will generate a horizontal velocity near the ground which is the main objective of this work to determine. There is evidence [1,2,3] that the mass fire will consist of local fires of the size of the length scale determined by Eq. (1b). We expect that the ground wind generated by the cumulative massive thermal plume is much greater than the winds generated by the local fires at their base. Therefore, this situation can be simulated by using a pure buoyant plume representing the buoyant flow above the flame height and having a diameter representing that of the mass fire. We note that the dynamics and similarity of this flow will be the same for any size turbulent buoyant plume.

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There have been a number of studies on the flow dynamics of large-scale buoyant plumes [e.g., 4-6]. It has been observed that the flow contracts as it moves away from the source reaching a minimum radius, or neck, beyond which the plume begins to expand eventually forming a pure plume with the radius growing linearly with height and that the height of the neck is approximately equal to one source radius and the neck has a radius of approximately half the source radius. The air entrainment into a large-scale thermal plume, which is critically important in understanding the flow dynamics of the thermal plume, was however not measured in these studies. In a more recent study [7], the volume flux of a buoyant turbulent plume emerging from a large area source with low initial momentum flux was measured and it was found that the volume flux in the plume increases linearly from the source to the neck, which is consistent with the finding in [1].

The objective of this study is to examine the mass entrainment and the related wind generated by the massive thermal plume based on similarity analysis and computational fluid dynamic (CFD) modelling. It is worth noting that this similarity and numerical analysis for the mass entrainment has been recently validated [7] experimentally providing a further incentive to validate the correlation for the wind generated near the ground.

The paper is organized in the following way. We first use similarity analysis to make a prediction for the mass entrainment and the related wind generated by the massive thermal plume. Next, we numerically simulate using Fire Dynamics Simulator (FDS) [8] the thermal plume and the wind induced near its base by using helium release as a buoyancy source, where these calculations are validated by experiments using helium available in the literature for a source diameter 1m [9]. Subsequently, predictions are made for various plume source sizes and flow rates. Based on the results from all simulations with 3D circular sources, the maximum horizontal velocity is correlated with the fire source diameter and the equivalent heat release rate determined from the buoyancy of the helium flow. Finally, simulations are performed for a 2D case mass fire case, simulating a forest line front, where the source length is set in that direction the same as the computational domain while the fire source width varies.

2. SIMILARITY ANALYSIS

We remind the reader that fires [1] can be conveniently distinguished in three types as Fig. 1 illustrates: buoyant jets, pool fires and mass fires, where the distinction is based roughly on the fire Froude number defined as follows:

$$Fr_f = \frac{\dot{Q}g}{\rho_\infty c_p T_\infty D^{\frac{5}{2}} (\frac{\Delta T_f}{T_\infty} g)^{3/2}} \quad (2a)$$

Here ΔT_f is the mean temperature rise over the ambient as affected by radiation losses, efficiency and fluctuations. It is usually nearly constant (800 K) for hydrocarbon-based materials.

The heat release rate is taken here to be equal to the convective heat release rate which is related to the buoyancy flux (for example for Helium release) by the following relation

$$B = \frac{\dot{Q}g}{c_p T_\infty} \quad (2b)$$

Our focus here is the mass fires as shown in the bottom part of Fig. 1, which exist for $Fr_f < 0.01$. The flow generated in this situation is illustrated in Fig. 2. The flame height in this case is given by Eq. (1) being less than 10m independent of the source diameter as discussed following Eq. (1) so that the massive cumulative convective flow above the fire, as illustrated in Fig. 2 , is the main cause of the wind induced by the fire near its base. Our next task is to derive an expression for this wind speed near the base of the fire plume.

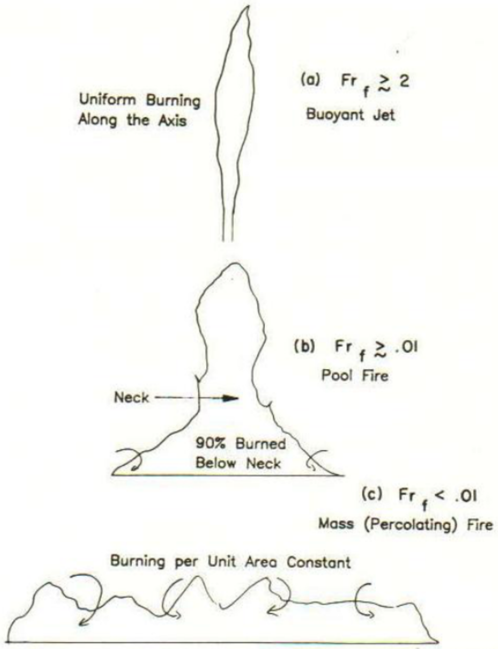

Figure 1. Three characteristic types of turbulent flames: buoyant jet, poof fire and mass fire delineated by their fire Froude number (Eq. (2a)).

The flow of the large convective fire plume consists of three regimes, one near its base, one in the necking area and one in the asymptotic regime, as shown in Fig. 2. The fire convective flow is conserved according to the following relation based on similarity of the flow:

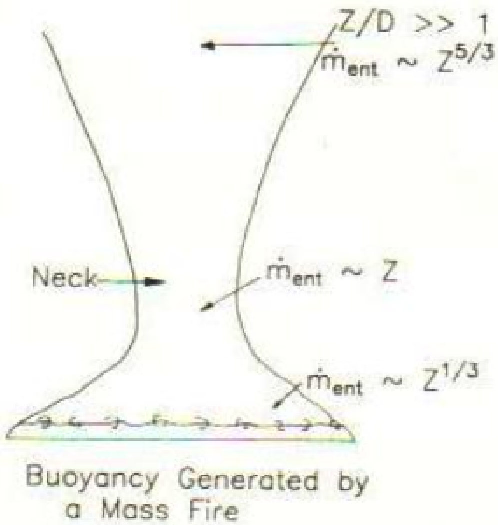

Figure 2. Illustration of different entrainment regimes for mass fires

$$\dot{m}_{ent}(Z)c_p\Delta T_c \sim \dot{Q} \tag{3a}$$

Here $\dot{m}_{ent}$ is the entrainment rate to a height Z and ΔT_c is the centreline excess temperature. The symbol ~ denotes that the sides of equation are proportionally related by a pure number.

The entrainment velocity at a height Z and the average entrainment velocity up to a height Z in buoyant flows are both given by :

$$U_{ent}(Z) \sim \sqrt{\frac{\Delta T_c}{T_\infty} gZ} \tag{3b}$$

but having different proportionality coefficients,

The mass entrainment rate up to a height Z is given by:

$$\dot{m}_{ent}(Z) \sim \rho_\infty U_{ent}(Z) A_e \tag{3c}$$

where the entrainment area A_e can be expressed by the following relations in the three regions of the massive plume:

$$A_e \sim \begin{cases} D^2 & \text{in the base region} \\ DZ & \text{in the necking region} \\ Z^2 & \text{in the asymptotic region} \end{cases} \tag{4}$$

By combining Eqs. (2) to (4) we can obtain the entrainment rate, the temperature rise and the velocity in the three regimes. We present here the entrainment and the velocity in the lower two regimes because these relations in the asymptotic regime are well known.

<u>Entrainment rate and centreline velocity near the base</u>

$$\frac{\dot{m}_{ent}}{\rho_\infty \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty}\right)^{1/3} D^{5/3}} \sim \left(\frac{Z}{D}\right)^{1/3} \quad \text{and} \quad U_{ent} \sim \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \left(\frac{Z}{D}\right)^{1/3} \tag{5a}$$

<u>Entrainment rate and centreline velocity near the necking area</u>

$$\frac{\dot{m}_{ent}}{\rho_\infty(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty})^{1/3} D^{5/3}} \sim \frac{Z}{D} \quad \text{and} \quad U_{ent} \sim \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \sim U_{wind} \qquad (5b)$$

Note that velocity in the necking area, Eq. (5b), is independent of height Z. It is also important to note that the entrainment rate correlation in Eq.(5b) has been validated by recent experiments in [7].

Based on the present analysis the wind induced velocity will be given by the second relation in Eq. (5b), which is the proposition to validate and find the proportionality coefficient in this work.

We proceed next with the development of the numerical simulation used to calculate the induced velocity near the ground. As we stated earlier, we do the calculations for a helium produced buoyant flow which scales the mass fire produced buoyancy in smaller size.

3. Numerical Details

Fire Dynamics Simulator (FDS, version 6) [8] was used for the present simulations with the dynamic Smagorinsky model for turbulence. Simulations were carried out for three 3D circular plumes 0.5, 0.8 and 1m in diameter and a 2D plume. The width, length and height of the computational domain vary for different cases but they were chosen in such a way that they have minimum effect on the simulation results. The circular source was approximated with small square sources. The total number of computational control volumes also varies for different cases, ranging from 4.5 million to 8 million. Grid sensitivity studies were carried out for each case showing further refinement of the grid size has negligible influence on the results. The total simulation time was 20s for all cases that is sufficient for the flow to reach the steady state and the results presented in this paper are those averaged between 10 and 20 s.

4. Results and Discussions

4.1. Validation of the numerical simulation by comparison with experimental data in [9]

Figure 3 presents a comparison of the 2D contour of the experimental data in [9] and predicted helium mass fraction. Generally, the predictions are in good agreement with the measurements. FDS predicts reasonably well the helium mass fraction at lower heights, i.e., within 40cm above the source, whereas it overpredicts the helium mass fraction at higher locations. The predicted prolonged helium profile can be explained by examining the prediction of the axial velocity as shown in Fig. 4. The maximum predicted axial velocity is 4 m/s occurring at 1m above the

Experiment

source compared to 3 m/s observed in the experiment at 0.7 m above the source.

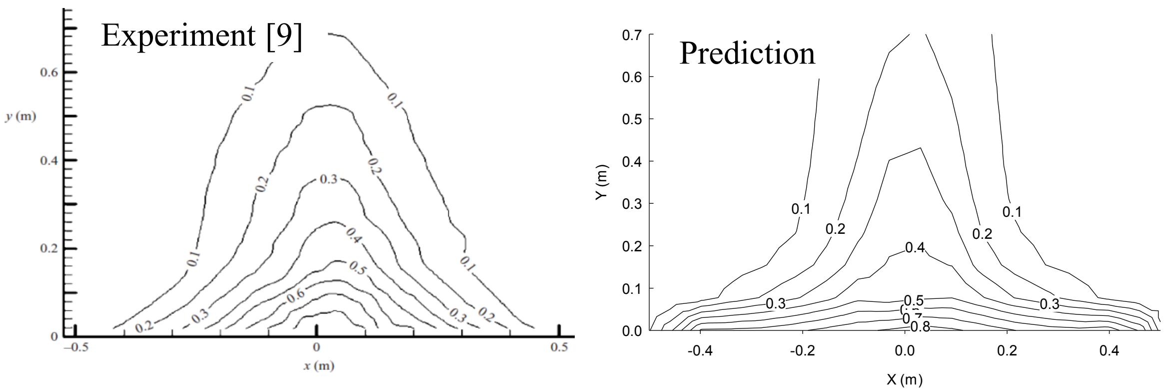

Figure 3. Comparison of experimental [9] and predicted helium mass fraction for a circular plume source with a diameter of 1m.

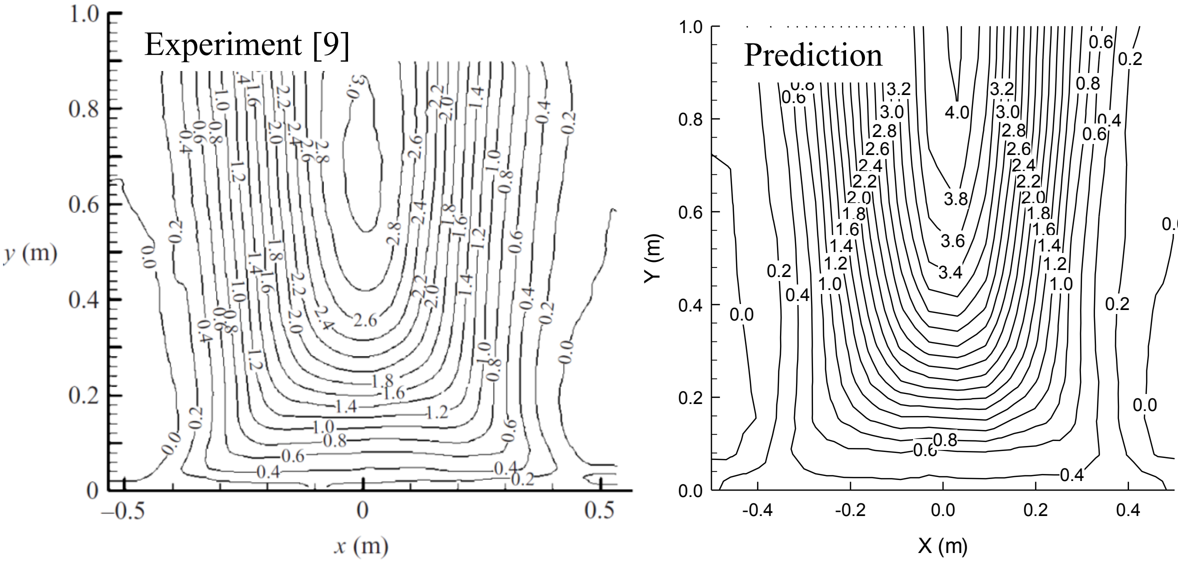

Figure 4. Comparison of experimental [9] and predicted vertical velocity for a circular plume source with a diameter of 1m.

Figure 5 shows the results for the horizontal velocity. The prediction is similar to the measurements except for a slight over-prediction of the maximum horizontal velocity, about 0.9 m/s compare to 0.7 m/s observed in the experiment. The maximum horizontal velocity occurs near the plume source and about 0.25 m from the center of the plume (i.e., half of the radius of the plume source) as reported in [4-6].

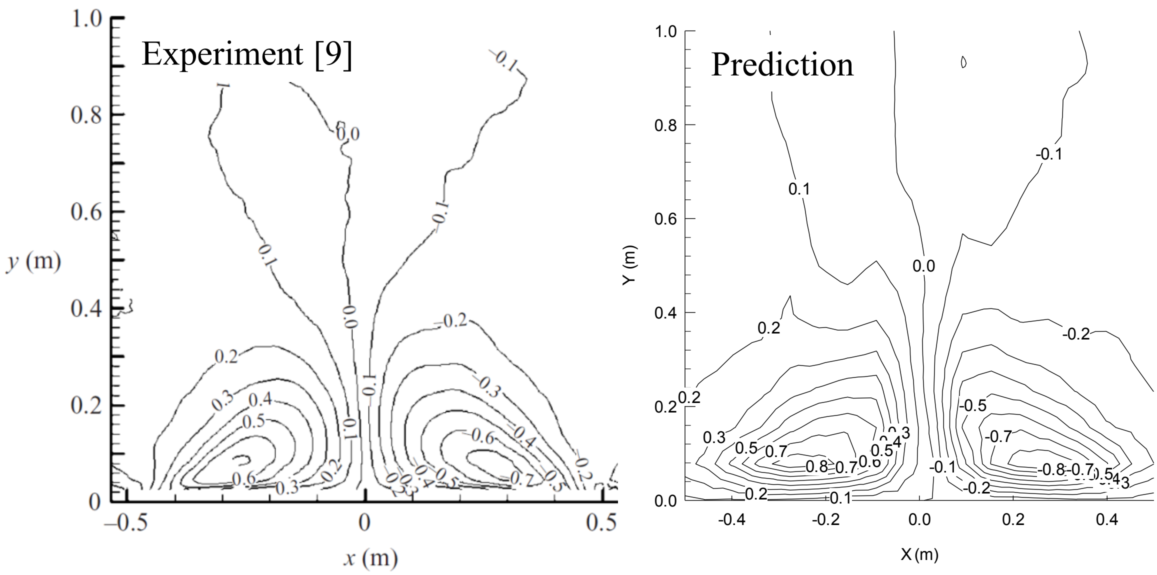

Figure 5. Comparison of experimental [9] and predicted horizontal velocity for a circular plume source with a diameter of 1m.

4.1. Maximum horizontal velocity in 3D mass fires

This section includes results for a 3D axisymmetric mass fire plume whereas the next section includes results for a 2D mass line fire.

Having established confidence in the computational simulation, we proceed next to calculate the maximum horizontal velocity induced by the helium buoyant flow. The relation of the helium flow rate to the corresponding heat release rate is given by

$$\dot{V}_{He} = \frac{1000\dot{Q}}{\rho_\infty c_p\left(\rho_\infty - \rho_{He}\right)} \approx 3.3\dot{Q} \qquad (6)$$

where $\dot{V}_{He}$ is the volume flow rate of helium in liter/s, and $\dot{Q}$ is the heat release rate in kW.

The maximum induced horizontal velocity is determined as the average of absolute values of the maximum horizontal velocity from diametric opposite (upstream and downstream) sides near the base of the plume. We use the prediction of Eq. (5b) to correlate these numerical results dropping for convenience the value for the ambient properties and the gravitational acceleration

$$\frac{g}{\rho_\infty c_p T_\infty} = 0.027\ m^4/s^2/kJ \qquad (7a)$$

Therefore, we plot the maximum induced velocities in Fig. 6 versus a reduced heat release rate parameter $(\dot{Q}/D)^{1/3}$ for all the simulations carried out in this study (i.e., different source diameters and HRRs). The result verifies our similarity analysis as all the data collapsed onto a single line having the following correlation:

$$U_{max} = 0.22(\dot{Q}/D)^{1/3} = 0.73\left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \qquad (7b)$$

Here velocities are in m/s, heat release rates in kW and diameters in m.

This result is significant because it provides a direct means to estimate the induced velocity from a turbulent plume if the heat release rate (or the flow rate for an inert plume) and dimensions of the source are known.

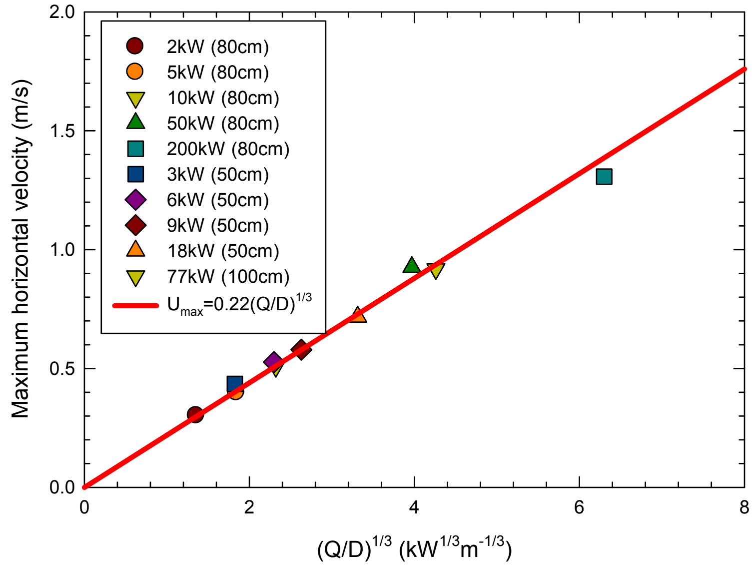

Figure 6. Maximum horizontal velocity plotted against the reduced normalized heat release rate, $\left(\dot{Q}/D\right)^{1/3}$, where D is the diameter of the source.

4.2 Maximum horizontal velocity in 2D mass line fires

In this section we extend the numerical calculation for a simulation of 2D mass fire merged buoyant flow which develops when the width of the line fire is large, for example more than 500m. In the analysis we vary the width and keep the length of the line fire constant at L= 2 m. We designate the length L as D in the correlations.

4.2.1. Vertical velocity for validation

For a 2D plume, the simulations are still three dimensional, but the length of the plume source was set as the same as the computational domain in that direction (2m) whereas the width of the plume source and the flow rate were varied. Simulation results at different cross sections verify that the flow is essentially two dimensional. Figure 7 shows the vertical velocity at different initial helium velocities/HRRs for the case with the width of the source equal to 0.4 m. The flow accelerates quickly after its release before reaching its maximum value. It is known that for a 2D plume the vertical velocity does not decrease after reaching its maximum as verified in Fig. 7.

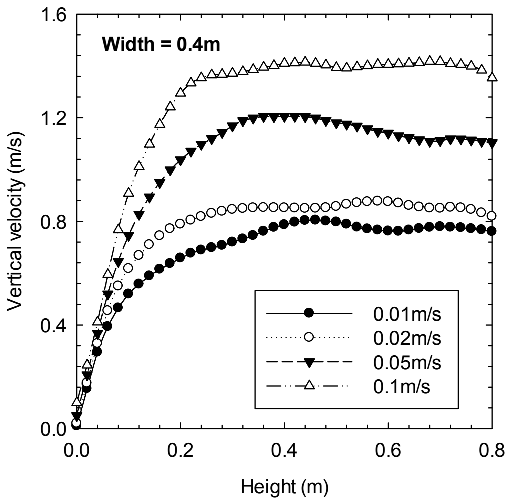

Figure 7. Vertical velocity at different initial helium velocities/HRRs for the 2D plume with a source width equal to 0.4 m.

Figure 8 plots the maximum vertical velocity for all cases (four widths of the plume source × four heat release rates as a function of $\left(\dot{Q}/D\right)^{1/3}$, where D is the length of source (2 m for all cases) and the result indicates that for a 2D turbulent plume the following relation exists:

$$V_{max} = 0.65\left(\dot{Q}/D\right)^{1/3} = 2.16\left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \quad (8)$$

This value of the coefficient in Eq. (8) is in good agreement with the corresponding coefficient (0.62) measured in the far field of line fire plumes in [10].

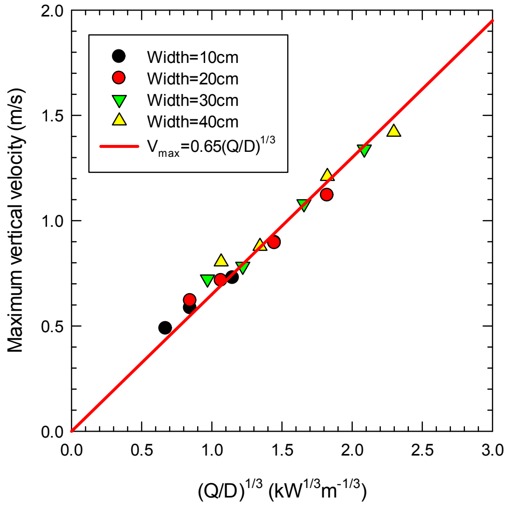

Figure 8. Maximum vertical velocity from a 2D plume plotted against the reduced normalized heat release rate, $(\dot{Q}/D)^{1/3}$, where D is the length of source (2 m for all cases).

4.2.2. Maximum Horizontal induced velocity in 2D mass fires

The maximum induced horizontal velocity is determined similarly as for the 3D plumes, i.e., the average of absolute values of the maximum horizontal velocity from opposite (upstream and downstream) sides near the base of the plume. The maximum horizontal velocity for the 2D plume is plotted in Fig. 9, where we note that the same correlation as found in the 3D plume applies to the 2D case as well, namely $U_{max} = 0.22(\dot{Q}/L)^{1/3} = 0.73\left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty L}\right)^{\frac{1}{3}}$, with the characteristic length being the length of the plume source for the 2D plume as opposed to the diameter of the source for the 3D plume. There is some scattering for the case with the width of the source equal to 10 cm probably because the flow is not fully turbulent when the width of the source is small.

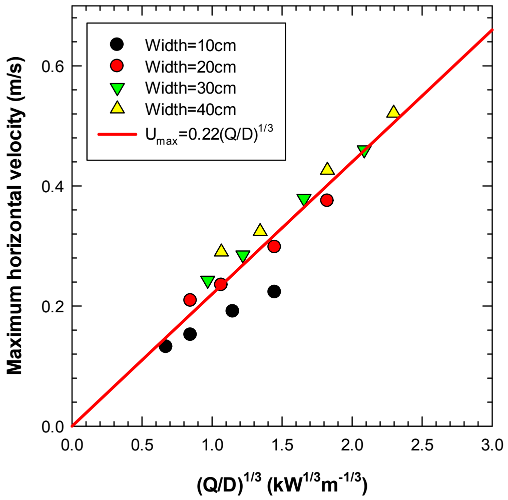

Fig. 9. Maximum horizontal velocity from the 2D mass fire plumes for various widths plotted against the reduced normalized heat release rate, $(\dot{Q}/D)^{1/3}$, where D is the length of source L.

5. Concluding remarks

This work investigates the induced velocity near the ground in large-scale mass fires such as a deflagration following a nuclear explosion. This situation can be simulated using a buoyant plume of helium representing the buoyant flow above the flame height (less than 10m) of the large area fire deflagration (greater than 500m), see Eq. 1. A similarity and numerical study of turbulent helium buoyant plumes was presented. Fire Dynamics Simulator (FDS) was firstly validated against literature data and then used to deduce the correlation between the maximum horizontal velocity with the heat release rate (helium flow rate) and the fire source diameter. The key findings of this work are:

- A similarity correlation was developed for the entrainment and the velocity in a mass fire produced plume, Eqs. (5a) and (5b). The similarity for the entrainment has been recently validated experimentally [7]. Our solution allows us to predict that the wind induced velocity is given by $U_{ent} \sim \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}} \sim U_{wind}$.

- FDS is capable of predicting well the flow induced in non-reactive turbulent buoyant plumes [9] near the base (Figs. 2-4), but it overpredicts the vertical velocity to some extent resulting in a prolonged helium profile compared to experimental data.
- For both 2D and 3D plumes, the maximum horizontal velocity can be correlated to the heat release rate $\dot{Q}$ and a characteristic length, D, by $U_{max} = 0.22(\dot{Q}/D)^{1/3} = 0.73 \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}}$, where D is the source diameter for the 3D case and the length of the source for the 2D case (Figs. 6 and 9). As an example, we note that for large conflagration 1000 m in diameter having a heat release rate of 800kW/m^2, the induced velocity near the ground would be 18.83 m/s or 67.8 km/h (the flame height would be 5.9 m, see Eq. 1). These results can be applied in case of a nuclear deflagration, a case for which this work was funded for.
- The FDS prediction is further validated by verifying that the vertical velocity in a 2D simulated mass fire plumes does not decrease with height after reaching its maximum value (Fig.7) which agrees with experiments. Specifically, the following correlation exists for the vertical centerline velocity $V_{max} = 0.65(\dot{Q}/D)^{1/3} = 2.16 \left(\frac{g\dot{Q}}{\rho_\infty c_p T_\infty D}\right)^{\frac{1}{3}}$, where velocity is in m/s, heat release rate in kW and length in m and D is the length of the mass fire line plume.

Further work is anticipated to examine the effects on very large area fires of various imposed atmospheric winds including the possible generation of fire whirls.

Acknowledgements

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