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Influence of Ground on Jet Fire Extension

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A common accident in the industrial process industry is the puncturing of storage tanks or rupture of process pipelines containing gases. In these scenarios, the gas will escape the piece of equipment producing a single-phase gas jet. If the fluid is flammable, an ignition source is most probably encountered during the accidental scenario and a jet-fire can follow the leak. Free jets of hazardous gases and free jet-fires have been extensively analyzed in the past literature to assess their shape and extension for safety purposes. Similar analyses have been conducted to observe the effect on shape/extension of neutral jets if obstacles were present. Also, the effect of the ground proximity to the jet source has been studied. In general, the presence of obstacles and the proximity to the ground lead to enlarged hazardous areas, mainly because of the Coandă effect. In this work, flammable jets igniting and forming a jet-fire were considered. The effect of the ground proximity was analyzed, to observe the extension of the flame. Two opposed phenomena were supposed to act on the fire, differently from non-ignited jets: the Coandă effect having an attractive nature towards the ground and the buoyancy effect on the opposite direction. The relevant methane jet-fires case study was considered carrying out computational fluid dynamics (CFD) simulations using the Fire Dynamics Simulator software. The study considered both the jet source height from the ground and the gas relief flowrate effects. CFD results were summarized basing on simple dimensionless parameters to determine the eventual variation of jet-fire extension for preliminary safety analyses.

1. Introduction

The tendency of fire to adhere to near slopes and hills has been largely studied. This is due mainly to the Coandă effect, which is caused by inhibited entrainment of ambient fluid near the solid; the lack of entrainment on one side of the jet causes a pressure gradient to develop normal to the flow direction that causes the jet to attach to the surface (McLean, 2012). Extensive work has been done studying the Coandă effect in various applications, both in absence and presence of flame, for example nozzle flows (Shaari et al., 2015), high pressure jets of different materials interacting with the ground (Colombini et al., 2020), or with obstacles (Colombini and Busini, 2019, Colombini et al., 2021) for the former case and swirled flame (Singh and Ramamurthi, 2009) fire-wall interaction behaviour (Himoto et al., 2009, Gao et al., 2015, Ji et al., 2015), for the latter. These works are able to confirm that the Coandă effect is predominant in the case of vertical or horizontal no ignited jet and in case of vertical flame, that is in the case in which the buoyance and the flow has the same direction, but, for the Author's knowledge, there is not an extensive work made to see which is the behaviour of the flame when the buoyance and the Coandă effect are in contrast directions, that is for horizontal jet fire close to the terrain. In this work, the effect of the ground proximity is analyzed, to observe the extension of the flame in the presence of the two opposed phenomena. A parametric analysis was performed for sub-sonic methane jet-fires, by means of computational fluid dynamics using the software Fire Dynamics Simulator from NIST. The study considers both the jet source height from the ground and the flowrate of gas relief.

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2. Materials and methods

Methane jet fires were simulated using the freeware software Fire Dynamics Simulator (FDS) version 6.7.1 from NIST (McGrattan et al., 2017) which has been adopted in literature for the description of fire accidental scenarios (Florit et al., 2019, Florit et al., 2022). The software solves transport equations for mass, composition, energy, and momentum on a cartesian grid, which is appropriate for the simple geometry of the considered cases. Equations are solved in the framework of Large Eddy Simulations (LES); therefore these simulations can only be performed in the time domain. The simulation is thus run over an extended time, to reach the jet fire steady state condition (in terms of average length). The fire is simulated as an ideal combustion of methane, thus considering only complete oxidation to carbon dioxide, solely contributing to the radiative part of the energy equation (no effect of soot and by-products radiation is considered). The accidental scenario considered is the release of methane in the atmosphere due to a full rupture of a pipe. The released flowrate is equal to 2.1 kg/s of methane (considered to be not pre-mixed) at ambient temperature (18 °C). An atmospheric class D was considered with wind speed of 5 m/s at 10 m height. The wind speed profile is available in the FDS software, provided the computational domain extends in the positive z direction from the value of 0. The physical-chemical properties of all chemical species are available in the FDS default databank.
The computational domain is sketched in Figure 1, where the value of the orifice dimension, d, is equal to 0.145 m and the height of the release, h, is varied between 0.29 and 2.61 m. The domain is subdivided into four parts with different grid sizes to capture the jet shape at best, adopting the mesh strategy used in (Colombini et al., 2020). The core region of the domain is close to the methane jet source with grid size of dimension equal to d/4, then the first far filed (Far 1) has cell size of d/2, the second (Far 2) equal to d, and the last (Far 3) equal to 2d. These domains extend in the transversal direction equally as in height. The part of the domain that is below the level of the ground is not meshed. This way of constructing the computational grid guarantees that all cases have an equal domain height above the level of the orifice, while allowing the vertical position of the orifice to change. According to the height of the methane pipeline, the total number of cells of the domain ranged between roughly 1.45 and 1.98 million cells. It should be noted that, effectively, the orifice is square-shaped; this was done to reduce the computational complexity of the cases without any apparent advantage given by using a circular orifice (which requires more detailed meshing in FDS, which uses cartesian grids). A grid-independence analysis was conducted on one of the cases and halving the cell size (multiplying by 8 the number of cells) does not change the predicted results. Each simulation required roughly three days (on an Intel Xeon E5-2640 CPU with 20 cores and 126 GB RAM) to obtain at least 5.5 s of simulated time, long enough for all jet fires to reach a steady condition.

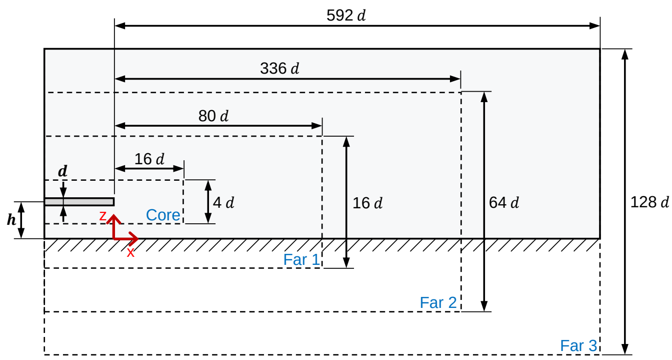

Figure 1: Computational domain for the jet fire simulations. d is equal to 0.145 m, h was varied between 0.29 and 2.61 m.

The results of the simulations were analyzed with the freeware software SmokeView and post-processed using the software Matlab® by observing the distribution of the methane volume fraction in the computational domain, especially on the x-z plane. The flame extension is computed as the maximum distance from the orifice at which the methane volume fraction (averaged over the last 2 s of simulation) falls below the lower flammability limit of methane (LFL, 4.4 vol.%). The same results can be obtained using the heat release rate per unit volume (HRRPUV) with a threshold value of 200 kW/m^3, the default flame visualization threshold of SmokeView. Heat flux and temperature were pointwise monitored during the simulations on the ground on a line corresponding to the x axis, to consider possible radiative-exposure scenarios where targets on the ground are of interest.

3. Results and discussion

The results of the simulations for the different values of h are reported in Figure 2 as contour plots, reporting the methane volumetric fraction from the LFL to pure methane. The contour plots of the time-averaged methane volume fraction show the well-known shape of a free jet fire, initially dominated by momentum (horizontal part) and eventually controlled by buoyancy (upward part) when the jet has no influence from the ground. The case for which h/d = 2 shows a jet fire impinging the ground and an increase in the width of the jet can be noted.

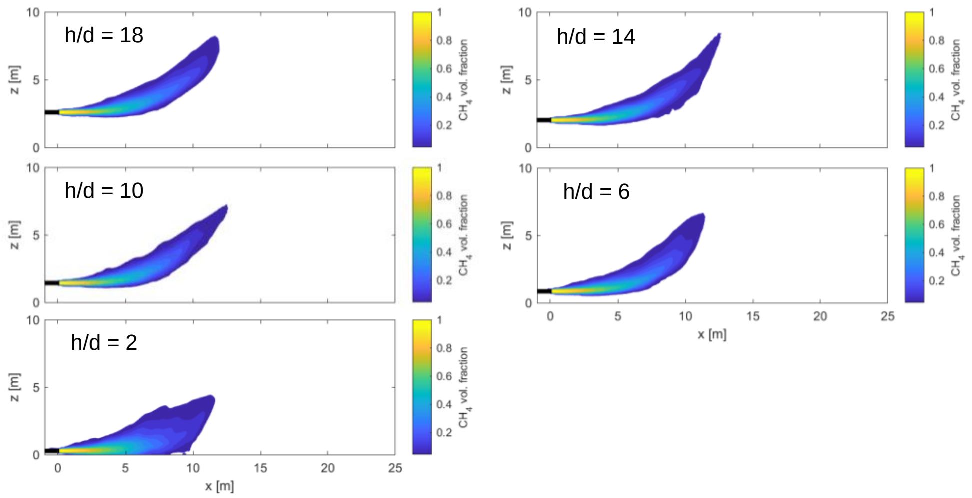

Figure 2: Visualization of the jet fire on the x-z plane as contour plot ranging from the LFL to pure methane for the various emission positions studied for a release of 2.1 kg/s of methane.

Notably, the Coandă effect does not seem to play a relevant role in extending the length of the jet fire, as observed instead for non-ignited high-pressure jets. This can be ascribed to the more important effect of buoyancy in ignited sub-sonic jets, driving the jet upwards and overcoming the downdriving Coandă effect.
The results of the simulations were validated by comparison with the correlation proposed by (Lowesmith et al., 2007) and (Palacios et al., 2020) in terms of free jet fire length and radiative heat flux.
Table 1 reports the numerical values of all jet fire dimensions, the heat release rate (HRR), and radiative power (QR) of the fire. The HRR value is needed to use the correlations evaluating the jet fire extension and radiative intensity for which the average of the values obtained, 96.4 MW, was used. The obtained average flame length, 12.1 m, is lower than the value calculated with the correlation proposed by (Lowesmith et al., 2007), 15.9 m, which is based on experimental data on natural gas (mainly containing methane). The correlation proposed by (Palacios et al., 2020) for jet length (based on experimental data collected under very different conditions) leads to a value of 12.9 m, thus in a better agreement with the results of this work. Correctly, the various jets produce similar values of power, as the same amount of material is released in the environment and methane is totally oxidized within the computational domain. The average radiative power obtained in the simulations is 12.1 MW in agreement with the result of 12.7 MW obtained with the correlation of (Lowesmith et al., 2007).

Table 1: Numerical results of the simulations for a release of 2.1 kg/s of methane at different heights.

H [m]	h/d [-]	HRR [MW]	QR [MW]	HE [m]	VE+ [m]	VE- [m]
0.29	2	98.0	13.2	11.7	4.21	0.29
0.87	6	96.8	11.9	11.5	5.87	0.29
1.45	10	93.9	11.6	12.6	5.87	0.36
2.03	14	95.1	11.5	12.8	6.45	0.36
2.61	18	98.1	12.4	12.0	5.65	0.36

The simulation for h/d = 2 leads to a value of the vertical extension towards the ground, VE-, equal to h, as the jet fire impinges the ground. The minor influence of the Coandă effect can be observed in the value of the vertical extension in the positive z direction, VE+, which is almost a constant for all cases except the one of h/d = 2, where the proximity of the ground tends to drive the jet downwards. This can also be noted from Figure 2, where the plume widths are similar for all cases except the one with the lowest release height, for which the width of the flame is larger.

Figure 4 reports the simulated heat flux along the x axis as a function of a dimensionless coordinate, x_{dl} (position divided by flame length). It can be noted that all investigated flames cause unsafe conditions for some targets on the ground (both buildings or people), but the heat flux decays quickly away from the flame (x_{dl} greater than 1), leading to safe conditions for buildings at $x_{dl} > 1.27$ and for people at $x_{dl} > 1.75$. With the exception of the fire impinging the ground, the heat flux on the ground has a maximum roughly at half flame length, as it would be expected from simplified radiation models, such as the point-source model. With such models the prediction of the flame impinging the ground would be impossible and would disregard convective effects, showing the superiority of a detailed analysis.

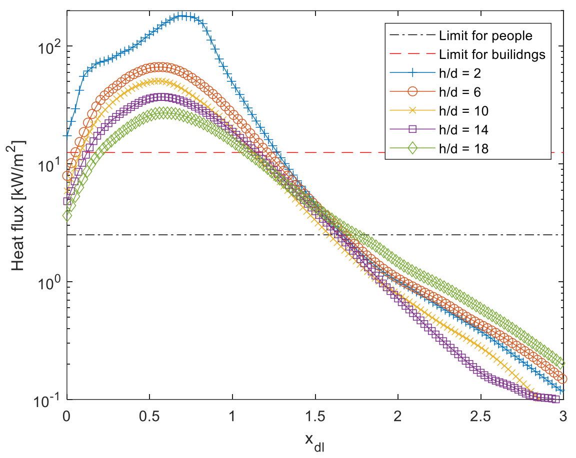

Figure 3: Calculated heat flux for targets at different positions on the ground, on the x axis of the computational domain for different release heights. Building safety limit is 12.5 kW/m^2, while people safety limit is 2.5 kW/m^2.

The effect of the release flowrate was also studied for the case h/d = 6, d = 0.145 m. Remaining in the framework of sub-sonic jets, the methane flowrate, F, was changed between 2.1 and 8.4 kg/s and the results are summarized in Table 2, reporting also the dimensionless horizontal extension, HE_{dl} (HE divided by the extension of a free jet). Figure 4 reports the flame shapes for the simulated cases.

Table 2: Numerical results of the simulations of different flowrates of methane at h/d = 6. Ignited free-jet length computed according to (Palacios et al., 2020), non-ignited free-jet length according to (Chen and Rodi, 1980), radiative heat flux QR from (Lowesmith et al., 2007). For all cases d = 0.145 m.*

F [kg/s]	HRR [MW]	QR [MW]	HE [m]	VE+ [m]	VE- [m]	HE_{dl}	QR* [MW]
2.1	96.8	11.9	11.5	5.87	0.29	0.89	12.8
4.2	187.9	24.2	15.9	5.94	0.44	0.97	24.7
6.3	272.5	37.0	20.7	6.09	0.87	1.11	35.8
8.4	387.3	56.8	22.9	4.49	0.87	1.09	50.8
2.1	Not ignited		40.4	1.88	0.87	2.07	

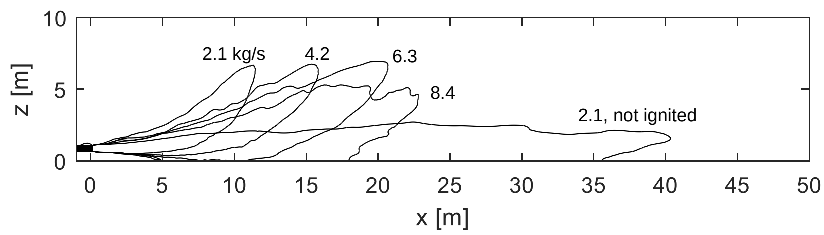

Figure 4: Extension (LFL isoline) of the jet fires and non-ignited jet at h/d = 6 for different flowrates.

Correctly, the obtained heat released is proportional to the flowrate, as methane is totally oxidized within the computational domain. Also, QR is roughly proportional to F and well agrees with (Lowesmith et al., 2007). At increasing flowrates, the convective effects (such as the Coandă effect) should become more relevant and produce wider jets. This is observed for the non-ignited jet which has a value of HE_{dl} larger than 1. Nevertheless, the buoyancy effects in ignited sub-sonic jets are always predominant in determining HE in the analyzed cases, in fact all the values of HE_{dl} are close to 1, meaning that all flames have a horizontal dimension similar to those of a free, undisturbed jet fire.

VE- correctly increases at increasing flowrate for ignited jets, as more air is entrained in the jet at larger emission velocities, until the jet impinges the ground (when VE- is equal to 0.87 m). The positive vertical extension is an indicator of the presence of the Coandă effect: at the largest flowrate (largest influence of convection), VE+ has the minimum value and the jet is driven downwards with an increase of its width, as it can be seen from Figure 4. This effect is similar to the one observed before for the simulations at different release heights, showing that jets extremely close to the ground and/or with a large release flowrate can be affected by the Coandă effect, but this influence is minor.

The relevance of buoyancy in determining the shape and extension of the jet-fire was further investigated qualitatively with two additional simulations characterized by h/d = 6 and F = 2.1 kg/s. The first one is a fictitious simulation with reduced gravitational acceleration (0.981 m/s^2). The second is a simulation with standard gravity in the proximity of a vertical surface at a horizontal distance of 6d from the emission point. The former simulation is aimed at reducing the buoyancy forces by ten times, while keeping the convective forces constant. The latter simulation aims at observing the Coandă effect on a vertical surface where the buoyancy force should not play a relevant role, as it is instead for horizontal surfaces.

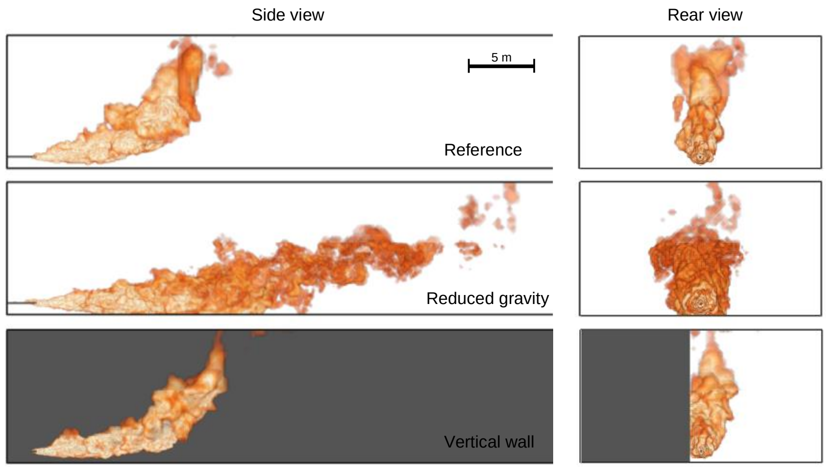

Figure 5: Instantaneous shape of the flames from the side and rear of the emission point with h/d = 6 and F= 2.1 kg/s in the reference case, in a fictitious case with reduced gravitational forces (g = 0.981 m/s^2), and in the presence of a vertical surface at 6d from the emission location.

The flame shapes reported by SmokeView are depicted with a view from the side and a view from the back of the emission in Figure 5 for the reference case and the two new simulations. It can be noted that the flame shape dramatically changes when gravitational forces are reduced (the length is more than doubled), confirming that the buoyancy effect counters and overcomes the Coandă effect in the reference case. The vertical surface influences the shape of the flame, as observed experimentally in other fire scenarios, extending the flame length slightly with respect to the reference case by prolonging the initial convection-driven part of the jet fire and reducing the width of the jet in the x-z plane projection. This suggests that convective effects become influent if not countered by buoyancy effects, as no buoyancy force is present in the direction perpendicular to the vertical surface. This can also be seen from the side view, where the flame is in contact with the vertical surface for more than half of its height. Further investigation will be needed to address the effect of vertical obstacles on the shape and dimensions of jet fires, where the Coandă effect may play a relevant role.

4. Conclusions

The effect of the ground proximity on ignited subsonic jets was studied using FDS to characterize the main dimensions of horizontal methane jet fires considering different release heights and flowrates. While non-ignited sonic jets are strongly affected by the ground (specifically the Coandă effect), non-ignited subsonic ones are marginally affected, as buoyancy acts contrarily to the down-driving influence of the ground. Therefore, safety assessment considering non-ignited jets will lead to conservative results for flammability problems when the

effect of ground proximity is considered if an ignition source is present close to the emission location, while it could be a good choice if the most likely scenario is a delayed ignition. The horizontal extension of the flame is almost unaffected by the ground, and it can be evaluated using the correlation proposed by (Palacios et al., 2020). A slight influence of ground on the vertical extension of the jet fire was observed at low flowrates when the release location is very close to the ground (h/d = 2) or at large flowrates (F = 8.4 kg/s) even at higher release locations (h/d = 6). The vertical extension is decreased when the jet fire is influenced by the ground.
The use of FDS provided accurate results (confirmed by the semiempirical correlations available in literature) both in terms of fire dimensions and radiation properties. Thus, these simulations can be directly used to assess radiation scenarios in detail without using standard models (e.g., solid flames, point source, etc.) which may oversimplify the case study.

Nomenclature

d – orifice dimension, m
F – released flowrate, kg/s
h – release height, m
HE – flame horizontal extension, m
HE_{dl} – flame dimensionless horizontal extension, -
HRR – heat release rate, MW
HRRPUV – HRR per unit volume, kW/m^3
LFL – lower flammability limit, %
QR – radiative power, MW
VE+ – flame vertical extension above release, m
VE- – flame vertical extension below release, m
VE – total vertical extension of the flame, m
x_{dl} – dimensionless coordinate, -

References

Chen, C.J. and Rodi, W., 1980. Vertical Turbulent Buoyant Jets – A Review of Experimental Data, first ed., vol. 4. Pergamon Press.
Colombini C.and Busini V., 2019, Obstacle influence on high pressure jets based on computational fluid dynamics simulations, Chemical Engineering Transactions, 77.
Colombini C, Martani A., Rota R., Busini V., 2020, Ground influence on high-pressure methane jets: Practical tools for risk assessment, Journal of Loss Prevention in the Process Industries, 67, 104240.
Colombini C., Maugeri G., Zanon G., Rota R., Busini V., "Unignited High-Pressure Methane Jet Impinging a Pipe Rack: Practical Tools for Risk Assessment", Journal of Loss Prevention in the Process Industries 69, 2021
Florit F., Favrin S., Rota R., Derudi M., 2019, Jet fires and reaction runaway interaction: A multiscale approach, Chemical Engineering Transactions, 77, 367–372.
Florit F., Busini V., Favrin S., Rota R., Derudi M., 2022, Reaction Runaway as a Domino Effect of Pool Fire Engulfing an Ethoxylation Reactor, Chemical Engineering Transactions, 91, 79–84.
Gao Z.H., Ji J., Wan H.X., Li K.Y., Sun J.H., 2015, An investigation of the detailed flame shape and flame length under the ceiling of a channel Proceedings of the Combustion Institute, 35, 2657-2664
Himoto K., Tsuchihashi T., Tanaka Y., Tanaka T., 2009, Modeling the trajectory of window flames with regard to flow attachment to the adjacent wall Fire Saf. J., 44, 250-258
Ji J., Fan C.G., Li Y.Z., Ingason H., Sun J.H., 2015, Experimental study of non-monotonous sidewall effect on flame characteristics and burning rate of n-heptane pool fires Fuel, 145, 228-233
Lowesmith B.J., Hankinson G., Acton M.R., Chamberlain G., 2007, Hydrocarbon jet fire hazards in the oil and gas industry and a simplified approach to assessing the hazards, Process Safety and Environmental Protection, 85(B3), 207–220.
McGrattan K., Hostikka S., McDermott R., Floyd J., Vanella M., Weinschenk C., Overholt K., 2017, Fire Dynamics Simulator User's Guide, NIST Special Publication 1019, USA.
McLean D., 2012, Understanding Aerodynamics: Arguing from the Real Physics (first ed.), John Wiley & Sons, Hoboken, New Jersey
Palacios A., García A., Rengel B., 2020, Flame shapes and thermal fluxes for an extensive range of horizontal jet flames, Fuel, 279, 118328.
Shaari K., Zilati K., Awang M., 2015, CFD Modelling of the Coanda Based Thrust Vectoring Nozzle, Springer International Publishing, New York, New York, 73-84
Singh N.K., Ramamurthi K., 2009, Formation of Coanda jet from sharp-edged swirl nozzle with base plate, Experimental Thermal and Fluid Science, 33, 675-682