Assessment of thermal radiation arithmetic's for jet flames

A study involving generic calculation methods concerning radiation from jet flames with the purpose to determine the safety distance for flame effects

Anne Lee Anderson

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Luleå University of Technology
Department of Civil, Environmental and Natural Resources Engineering

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Summary

Jet flames are commonly used as flame effects in pyrotechnical shows, and are also a possible risk in industries that uses pressurised flammable gas. For these users it is important to make fire safety engineering calculations. This project focus on jet flames that are used in pyrotechnic shows where, e.g. it is important to determine the safety distance to the audience. This study was initiated by SFX Controllers Sweden AB for their project to develop new flame effects that were to be permanently installed outdoors as a part of a larger media show. The flame effects developed is of the type sonic jet flames, which means that the exit velocity of the fuel is above the speed of sound. The flames are 15 respectively 25 meters high and the fuel used is Isopar L, a straight carbon chain including 11-13 carbons. The safety distance for a permanently installed flame effect is the distance from the flame to where the temperature of combustible materials does not exceed 47.2 ^{o}C above ambient temperature. This is the rule according to NFPA 160, which is the regulation that applies in this case.

A literature survey was made with the aim to find generic calculation methods for jet flames. Unfortunately, most publications are only based on experiments for sub sonic jet flames and the lack of information concerning sonic jet flames is striking. Based on information found, and assumptions when needed, calculations of the safety distance were made. Using the equation, $\varepsilon_s \sigma (T_r^4 - T_{AST}^4) + h_c (T_g - T_{AST}) = 0$, the maximum accepted radiation temperature could be determined. This was made for both a vertical and horizontal target. The accepted incident radiation could thus be computed. By dividing the incident radiation with the emitted heat flux, which was calculated by utilizing multiple expressions found in publications, the maximum accepted view factor to gain the required T_{AST} could be calculated. Calculations of the view factor as a function of the distance was also made. The calculated value of the maximum accepted view factors was than compared to the calculated view factor as a function of the distance for each specific flame for both a vertical and horizontal target. These calculations were made for a 15 meter and 25 metres cylindrical flame, respectively, and for both a vertical and horizontal target. Further, calculations were made at floor level and for each meter elevated as well as for each decimetre away from the flame. The farthest distance to the point where the view factor calculated for each specific flame for various distances is equal to the maximum accepted view factor is the safety distance. This resulted in a safety distance of 48 metres for a 15 meter and 64 metres for a 25 meter sonic jet flame.

Expressions to determine the mass flow rate and the energy release rate were found in earlier publications. However, no expression to calculate the flame temperature for jet flames was found. Hence an assumed flame temperature of 1200 ^{o}C was used in this project. Further, earlier studies have been made for small jet flames and are often based on propane as fuel. This complicated the determination of the safety distance for the specific jet flames of this project. The lack of information about generic calculation methods for large sonic jet flames as well as the fuel used made multiple assumptions needed. All assumptions have been made for the margin of error to be on the safe side. Thus, the calculated safety distance can be assumed to well fulfil the requirement in NFPA 160 that the temperature of combustible materials must not become higher than 47.2 ^{o}C above ambient temperature.

This study shows that there is a lack of information concerning computation of fire safety engineering calculations for jet flames. This is valid for both sub sonic and sonic jet flames. Further researches are recommended to develop expressions to calculate the flame temperature, the mass flow and the energy release rate for a general jet flame independent to size and which fuel used. This would enhance the safety when jet flames are used as flame effects in pyrotechnical context as assessed in this project. A better understanding of the thermal radiation and the geometry of jet

flames based on the outlet orifice and velocity, i.e. pressure, is expected to ease the designer of industrial facilities where the risk of occurrence of jet flames exists.

Key words: Jet flame, view factor, incident radiation, radiation temperature, safety distance

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Nomenclature

List of symbols

A_b	Burning area of the fuel	Unit: m^2
A_f	Area of the flame	Unit: m^2
d	The orifice diameter	Unit: m
D	The fuel source diameter	Unit: m
F_{2-d1}	View factor from surface 2 to an infinitive small surface 1	
Fr	Froude number	
g	Gravitation	Unit: kg/s
ΔH_c	Heat of combustion	Unit: MJ/kg
ΔH_{eff}	Effective heat of combustion	Unit: MJ/kg
K	Constant used in McCaffery plume equation	
L	The flame height	Unit: m
$\dot{m}$	Mass flow rate	Unit: kg/s
$\dot{m}''$	Mass flow per unit area	Unit: kg/(s m^2)
$\dot{m}_f$	Mass flow of fuel	Unit: kg/s
$\dot{m}_g$	Mass flow of gases	Unit: kg/s
$\dot{m}_{o_2}$	Mass fuel of oxygen	Unit: kg/s
n	Constant used in McCaffery plume equation	
$\dot{q}$	Energy release rate	Unit: W
$\dot{q}_c$	Energy release rate for combustion	Unit: W
$\dot{q}''_{emi}$	Emitted heat flux	Unit: W/m^2
$\dot{q}''_{inc}$	Incident radiation	Unit: W/m^2
$\dot{q}_{inc,2-d1}$	Incident radiation from surface 2 to an infinitive small surface 1	Unit: W
Re	Reynolds number	
S	Lift-off distance	Unit: m
T_∞	Ambient temperature, room temperature	Unit: K
T_{AST}	Adiabatic surface temperature	Unit: K
T_f	Flame temperature	Unit: K
T_g	Gas temperature	Unit: K
T_r	Radiation temperature	Unit: K
u_j	Gas velocity	Unit: m/s
z	A certain point within L	Unit: m

ε_f	Flame emissivity	
ε_s	Surface emissivity	
σ	Stefan-Boltzmann's constant, 5.67*10^{-8}	Unit: W/m^{2}K^4
τ	Atmospheric transmissivity	
φ_s	The fraction of heat radiated	
χ	Combustion efficiency	

Glossary

NFPA	National Fire Protection Association
Sonic jet flame	Jet flames with an exit velocity above the speed of sound
Subsonic jet flame	Jet flames with an exit velocity below the speed of sound

Introduction

Background

Pyrotechnical shows are today common in the entertaining business, and the safety aspects that one need to bear in mind when executing a show of this character are multiple. Flame effects are used as a vital part of stage pyrotechnics, both when performing indoor and larger outdoor shows. To ensure a safe performance it is among other things of greatest concern that flame effects are placed so that no combustible material can ignite from either direct contact with the flame or from the heat radiated from the flame. Since flame height and its effect can be altered by adjusting the exit pressure of the fuel a specific safety distance for each produced flame effect is hard to determine. The main problem with this is that the flame effects used are often in form of sonic jet flames. Up to now most studies made concerning jet flames regards jet flames in subsonic regiments, whilst there is a lack of studies concerning sonic jet flames and mathematical formulations for radiation from these cases are limited [1]. This makes pre-determination of temperatures, safety distances, flame heights etc. a challenge. Henceforth, most earlier studies include smaller jet flames (2.5 metres) and only a few handle larger flames (up to 10 metres) [1]. Relatively simple mathematical formulations would therefore be of great interest in order to make calculations for jet flames of any size.

SFX Controllers Sweden AB is a company that develops different pyrotechnical equipment and effects, including flame effects. One project was the development of new flame effects of larger scale. These flame effects will be a part of a larger outdoor multimedia show and the flames will be 15 m and 25 m high, respectively, with an outlet orifice diameter of 12.75 mm. The flame effects will be of the type diffusion jet flames i.e. the fuel and oxygen are separated at the beginning, opposite to premixed flames. The jet flames will also be sonic, which means that the exit velocity is faster than sound. The flame effects will be developed according to the standard NFPA 160 Standard for the Use of Flame Effects Before an Audience. Among other things one requirement according to NFPA 160 is that no combustible material in the surrounding shall exceed 47.2 °C above ambient temperature due to the affect from the flame. Ergo, calculations must be made to be able to determine the closest acceptable distance between the flame and combustible materials. The fuel used is Isopar L, a mixture of carbohydrates that has no tabulated values of parameters needed to calculate e.g. the energy release rate and the flame temperature, making such calculations somewhat uncertain.

Further, although accidental jet flame fires often are relative small it is shown that jet flames constitute a large risk factor due to the possibility for a chain reaction, e.g. that can lead to a larger fire or explosions [1]. Therefore, studies of sonic jet flames, i.e. jet flames with an exit velocity above the speed of sound, are also of great interest according to Palacios, Munoz and Casal [1] in a general fire safety perspective. The possibility to analyse the geometry of the flame, flame temperature and heat release rate as well as the potential damage from a jet flame with a small margin of error can lead to optimizing the construction.

Purpose

The development of a flame effect plan for permanent installed large-scale flame effects constitutes a part of this project. The aim is to ensure the development of a flame effect system that satisfies the demands according to NFPA 160. The main objective with this study is to determine at which distance from a flame the temperature of combustible materials reaches 47.2 °C above ambient temperature, as stipulated by NFPA 160. One goal is to investigate if it is possible to accurately determine the properties of a jet flame without large scale experiment or computational simulations. Spread sheet calculations made will be based on earlier studies concerning jet flames. The aim is to derivate an expression for the flame temperature depending on the orifice diameter and the flame

height. Due to that the flames that is studied in this project is adapted to be placed outdoors with no construction placed above, only the horizontal distance will be studied. The influence of the view factor as well flame emissivity will be taken in consideration with the purpose to analyse the potential limitations with the simplified approaches that is often used in fire safety calculations. The purpose with this project is also to shed light on the possibilities, the risks and the limitations by utilizing arithmetic's calculations for fire safety calculations concerning jet flames. The goal is additionally to find a suitable calculation method for general jet flames. Further, the goal is that the result from this project will ease both planning of pyrotechnical shows and permanent installations of flame effects, as well as with design of certain constructions where the risk of jet fires is palpable. Finally, the aim is that the result from this project will be utilized in upcoming studies concerning jet fires in sonic regimes of various sizes.

Hence, the main research objectives are as follows:

- At what distances from the flames of focus are it acceptable to place combustible materials?
- Is it at present possible to calculate jet flame properties without large scale experiments or computer simulations?
- Can a simplified generic calculation approach be developed for a general jet flame based on existing studies and information?

Method

Methods used during this project is mainly literature survey and spread sheet calculations. Comparison of the gathered information as well as the result from earlier found calculation methods is made. This will help determine the reliability of found arithmetic's methods as well as the possibility to utilize earlier studies as a base for a general expression for a jet flame. Further, a literature search for fuel properties of chemical compounds of the same characteristics as the fuel (alkanes) has been performed to ensure that reliable constants for Isopar L in the computation of the flame properties is used.

Delimitations

In this project the found equations and calculation methods are only applied on the jet flames of focus, i.e. a 15 meter and a 25 meter high jet flame with the exit orifice of 12.75 mm and in the sonic regime. The fuel used for these flames are Isopar L. Calculations will however be conducted with the values of the fuel specific parameters for the fuel Dodecan. This due to the lack of information about Isopar L and the assumption of similarity in values with Dodecan. Calculations for flames with a different flame height, based on another fuel and in sub sonic regimes have thus not been made. Due to this, the presented information regarding calculation methods for sub sonic jet flames is fairly limited in this report.

Further, delimitation have also been made to only determine the safety distance at a horizontal distance from the flame. This since the flames is placed outside and no combustible materials are assumed to be placed above.

Theory

The literature survey revealed a significant lack of research on sonic jet flames, which has been denoted in earlier studies as well. However, multiple studies concerning subsonic jet flames or small-scale jets have been made. [1] In the same study, it has been stated that it would be of great interest to have an expression to determine flame length for sonic jet flames. This is due to that accidental fires caused by jet flames often are formed by sonic jet flames, because the gas under these conditions normally is released at such pressure that sonic flow is reached. [1] In this chapter, the gathered information will be presented with focus on information that is of interest for sonic jet flames. Previous investigations, studied as a part of this project, are often based on experiments where propane has been used as a fuel. The equations reported from these experiments have been applied to Isopar L with the purpose of analysing the possibility of utilizing documented arithmetic's methods general for arbitrary jet flames independent which fuel that is used. Additionally, a short description of the NFPA 160 guidelines that is of most interest for this project is presented.

NFPA 160

NFPA 160 is a standard that controls the development and utilization of flame effects in front of an audience. The requirements differ depending on if the flame is temporary or permanently installed. In this study the flame effects are considered to be permanently installed. Only the guidelines which are of interest in a fire safety calculation aspect will be presented below. For mechanical safety guidelines, see NFPA 160 [2].

The requirements that is of interest for the fire safety engineering calculations made in this project is that the temperature of combustible materials is not allowed to exceed 47.2 °C above ambient temperature due to the effect from the flame [2]. The definition of which temperature that NFPA 160 is referring to is not clarified within the standard. In this project, the temperature is assumed to be the adiabatic surface temperature, denoted T_{AST}. T_{AST} is defined as the temperature of a surface which cannot absorb any heat [9]. It is an artificial effective temperature which is a weighted average value of the gas temperature and the radiation temperature depending on the surface emissivity and the convection heat transfer coefficient. It is the highest temperature a surface can obtain under constant heating conditions. [9] Therefore, the temperature of a real material surface is lower than the adiabatic surface temperature, and the distance calculated are on the safe side. T_{AST} has thereby been chosen to be set as the determining factor in this project so that a safety distance independent to a specific material can be determined.

When developing a new pyrotechnical flame effect system a "flame effect plan" is required to be established according to NFPA 160, where e.g. the flame effect system is described and the safety features are presented. Such a plan, including the jet flames of focus in this project, was produced for a system created by SFX Controllers (Appendix A). The technical aspects of the flame effect plan are not described further in the theory chapter of this report or presented in the result chapter. The focus of this report is on the determination on the safety distance and fire safety engineering calculations that is also part of the flame effect plan.

Jet flames

When combustion occurs of a fuel which is continuously released with some significant momentum in a certain direction a turbulent diffusion flame develops, known as a jet flame [6]. Commonly, the turbulent strain rate is of such magnitude in the flammable parts of the shear layers at the edge of the jet in the initial part of the jet that no combustion can occur [4]. The distance from the exit orifice to the bottom of the visible flame, that is the point where combustion is possible, is referred to as

the lift-off distance [1,4,5]. Together they add up to the total flame height. Figure 1 below shows a typical jet flame set-up with the orifice and the lift of distance.
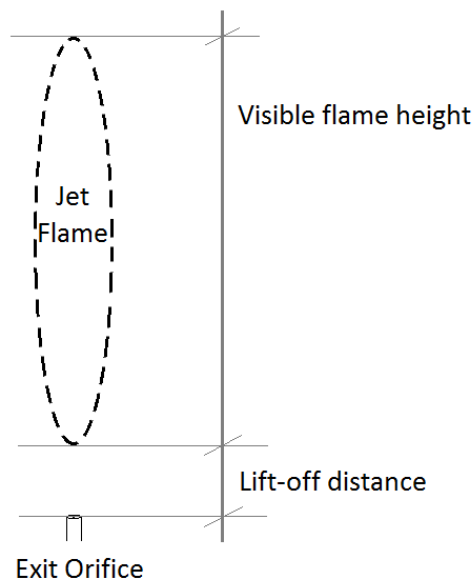

Figure 1: Jet flame

Multiple factors affect the features and properties of a jet flame. For instance, the flame height relates to the orifice diameter and the mass flow rate. Studies show that the flame height increases with the mass flow rate for a given orifice diameter, and for a given mass flow rate the flame height increases with the orifice diameter. [1] The size of the orifice has however according to some studies shown no effect on the incident radiation which is received by a target [5]. The same study has also reached the conclusion that the radiation intensity increases with the flame size.

Many authors have chosen to study the dimensionless value given by dividing the flame height with the orifice diameter. Additionally, it has been determined in earlier studies that when calculating the radiation from jet flames it is the geometry of the visible flame that is relevant [1]. Thus, if the visible flame height is unknown and only the total flame height can be predicted, the possibility to calculate the lift-off distance is mostly relevant. This because, together with the flame height, the lift-off distance determines the position of the flame which radiate heat to the surrounding environment. According to the research of Palacios et. al. [1] the average values for flame height and the lift-off distance were obtained with the intermittency criterion, which originally was developed by Zukoski et al. The definition of the intermittency is according to Zukoski et al. the fraction of time during which at least part of the flame lies above Z, where Z represents an elevated horizontal plane above the burner. Palacios et al. [1] has chosen to define the intermittency as the fraction of time when the flame height is at least higher than L (the mean flame height) and the lift-off distance is higher than S (the mean lift-off distance). Hence, when the intermittency equals to 0.5 the average values of the flame height and lift-off distance is reached. Froude number (Fr) or Reynolds number (Re) can be utilized to determine a reliable estimation of the height. [1]

Further, if the fuel utilized is gas or two-phase flow (gas-liquid mixture) will also affect the jet flame main features. Due to the increase of fuel mass flow rate if the fuel utilized is a gas-liquid mixture the flame will be larger. The flame will also be more luminous, and the fraction of heat irradiated will be

considerable higher. [5] Moreover, the presence of liquid droplets in the fuel will result in less efficient combustion. If gas fuel is utilized instead, the combustion will be more efficient, the emissive power will be comparatively low and the flame will be significant less luminous. [5] Additionally, the emissivity is found to be significant larger for jet flames in general compared to pool fires [14].

Subsonic and sonic regimes

Jet flames can be divided into two categories depending on velocity properties; jet flame in subsonic regimes and in sonic regimes. Subsonic regimes are flames with a velocity lower than the velocity of sound and flames in sonic regimes are flames with a higher velocity [3]. Generally sonic velocity is reached when the pressure at the fuel source exceeds 2.0 bar [4]. Ergo, the pressure at the fuel source determine the exit velocity [1,4], and when referring to velocity in this context, it is the exit velocity that is of interest. If a flame is in subsonic regimes or sonic will have an impact on vital properties. E.g. for flames at lower velocities buoyancy becomes important while in higher velocities the momentum of the fuel vapour mainly determines the flames behaviour [1]. The turbulent straining and shearing in the expansion region of the flow at the edge of the jet, where the mixture is flammable, is much too high for a flame to exist, whilst the fuel and air mixture in the centre of the jet is too rich to support combustion. Only after the jet has expanded and atmospheric pressure is achieved will the strain rate in the flammable region at the edge of the jet be reduced so that the first turbulent burning can be established – at the flame lift-off point. [11] Once the sonic condition has been achieved, the fluid velocity cannot be further increased and remains constant at the speed of sound. Nevertheless, as occurs with flame length, larger lift-off distances can still be obtained (using a specific outlet orifice diameter) if the gas pressure inside the pipeline continues to be increased.

Mathematical calculation theories

Unfortunately no explicit method for calculating the jet flame temperature has been found during the literature survey of this project. Hence several alternative equations reported in the literature are assessed below with the aim of finding a solution to compute safe conditions for pyrotechnics performance.

The energy release rate ($\dot{q}$) from a flame can be calculated in different ways depending on known parameters. Depending on the conditions $\dot{q}$ can be determined based on oxygen consumption calorimetry. This approach is based on that for most fuels and materials a relative constant amount of energy is released per unit mass of oxygen consumed [8]. Generally the energy released is 13100 kJ per kilogram oxygen consumed and for many hydrocarbon it is considered to be accurate to about ± 5 % [8]. The mass fraction of oxygen in the air is 23 %, and according to earlier publications the mass fraction after burning settles at an average value of around 15 % [8]. This means that combustion can occur when the mass fraction in air is between 23 and 15 %. An expression for the energy release rate based on the mass flow of gases for the studied fuel can thereby be developed, see equation 1, where the difference of the mass fraction of oxygen before and after the burning is included (i.e. 23 % to 15 %).

$$\dot{q} = 13100 * (0.23 - 0.15) * \dot{m}_g \qquad (1)$$

where $\dot{m}_g$ is the mass flow of gases [kg/s] and 0.23-0.15 is the mass fraction of oxygen consumed in the air. This gives $\dot{q}$ in kJ/s, which equals kW. Another way to determine $\dot{q}$ based on oxygen consumption calorimetry is to determine the total amount of oxygen reacting and multiply it with 13100 kJ. The reaction formula for combustion of a specific fuel can be utilized to calculate how much oxygen that is required to complete combustion. The known fact that for each kilogram oxygen

13100 kJ energy is released, which when multiplied with the total amount of oxygen consumed per second ($\dot{m}_{O_2}$, [kg/s]) for the specific amount of fuel used gives.

$$\dot{q} = 13100 * \dot{m}_{O_2} \qquad (2)$$

If the effective heat of combustion (ΔH_{eff}) and the mass flow rate of fuel ($\dot{m}_f$) is known the energy release rate can be determined by the equation below [8].

$$\dot{q} = \dot{m}_f * \Delta H_{eff} \qquad (3)$$

Where $\dot{m}_f$ is the mass flow of fuel given in kg/s and ΔH_{eff} is given in MJ/kg. If the effective heat of combustion is unknown $\dot{q}$ can be calculated by using the complete heat of combustion (ΔH_c) instead. The complete heat of combustion is determined by studying the chemical reaction of the fuel and oxygen. Usually complete combustion is not reached, therefore reduction must be made by considering the combustion efficiency (χ). The combustion efficiency is the ratio between the effective heat of combustion and the complete heat of combustion. For sootier fuels, the combustion efficiency is usually 60-70%. The equation for $\dot{q}$ is presented below. [8]

$$\dot{q} = \dot{m} * \chi * \Delta H_c \qquad (4)$$

There are multiple other alternative ways to determine the energy release of a fire, but most of them is not adapted to jet flames. Due to this they won't be presented in this study.

All equation above requires given information about the mass flow rate to be able to calculate $\dot{q}$. In a study conducted by Palacio et. al. [1] the measured mass flow rate from experiments was plotted against the flame height for various orifice diameters (Figure 2). The study included both jet flames in subsonic and sonic regimes. [1]
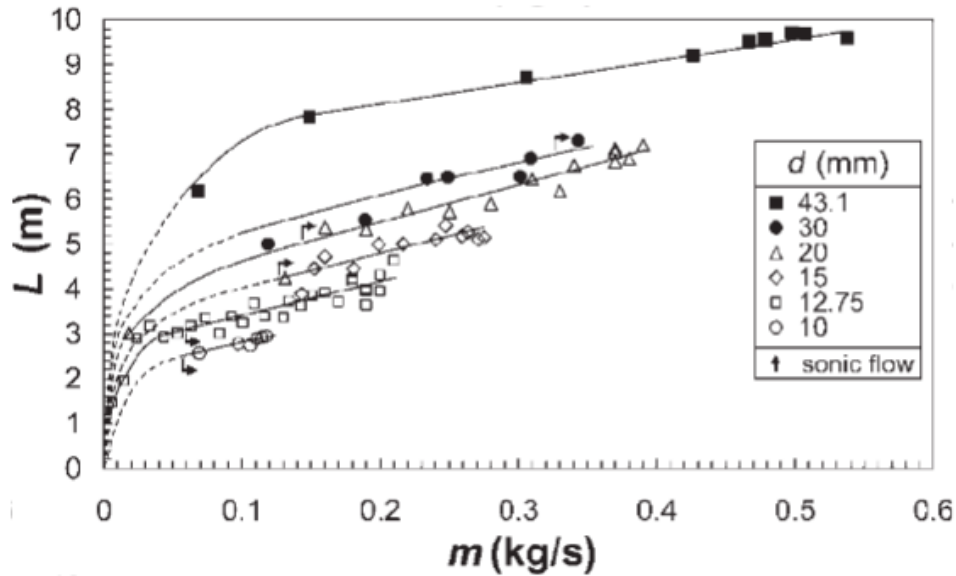

Figure 2: The relationship between flame lengths and mass flow rate of fuel for jet flames with various orifice outlet diameters (d). Experimental values are here based on a propane jet flame. Graph from [1]

Furthermore, in a different study by Gomez-Mares et. al. [5] a relation between L and $\dot{q}$ was derived from experiments (Figure 3) giving equation 5.

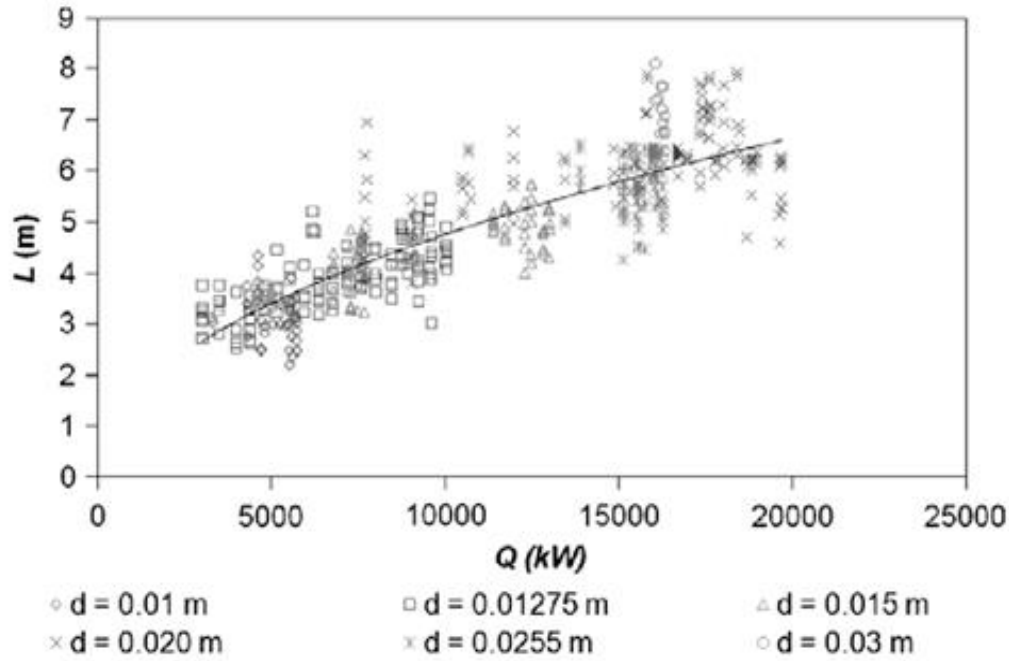$$L = 0.0562 * \dot{q}^{0.4819} \qquad (5)$$

Figure 3: The relationship between the flame height and the net heat released for jet flames with various orifice outlet diameters (d). Experimental values are here based on a propane jet flame. Adopted from [5]

Several studies have presented expressions where the flame height has been correlated with the Froude number in various ways in the buoyancy-dominated regime [1]. One common expression is presented below where the flame height (L) is a function of the Froude number (Fr) and the orifice diameter (d),

$$\frac{L}{d} = \alpha * F_r^b \tag{6}$$

Where α and b is given values that are pre-determined from experiment. Reported values for α varies between 14 and 40 with b being 0.2. [1] F_r can be calculated by equation 7 below [8].

$$F_r = \frac{u^2}{g*D} \tag{7}$$

where u is the flow velocity, g is the acceleration due to gravity and D is the diameter of the fuel source. However, this relation is only suitable for jet flames with subsonic exit velocities [1].

When $\dot{q}$ is known, the flame temperature can be determined. The interesting temperature in this study is the temperature within the flame. Therefore, McCaffery's plume equation (equation 8) can be assumed to be an alternative if the assumption is made that the entire flame will be in the continuous region. [8]

$$\Delta T_0 = \left(\frac{K}{0.9*\sqrt{2*g}}\right)^2 * \left(\frac{z}{\dot{q}^{2/5}}\right)^{2n-1} * T_\infty \tag{8}$$

However, there is a lack of information concerning equation 9 in relation to jet flames. The result generated from utilizing this approach is therefore uncertain.

Due to the lack of a specific equation for jet flames an assumed temperature will also be used. In order to be on the safe side when calculating the safety distance an adequate high temperature is chosen. The assumed temperature is 1200 °C and will be compared to the gained result from utilizing equation 8 and the most critical result will be promoted for usage.

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Further, the incident radiation intensity $\dot{q}_{inc}$ must be calculated to determine at which distance from the flame, the adiabatic surface temperature (T_{AST}) will be 47.2 °C above ambient temperature. T_{AST} is defined as the weighted average value of the radiation temperature (T_r) and the gas temperature (T_g) [9]. Thus, T_{AST} depends on T_r (or $\dot{q}_{inc}$) and T_g. Here the gas temperature close to the target is set to the ambient temperature as the flame is placed outdoors where vigorous mixing of the atmosphere occurs. To calculate T_{AST} the unknown parameter of $\dot{q}_{inc}$ (or as mentioned above - T_r) must therefore be determined. The heat radiated from the flame to a target surface is calculated with consideration to the view factor [9]. The definition of the view factor between two surfaces can be described as the fraction of radiation which leaves one surface and reaches the other surface directly [9]. The view factor takes in consideration both the vertical and horizontal distance from a flame to a target and the angle. Depending on the targets placement in respect to the flame different amount of radiation will reach the target. The view factor is thereby calculated differently depending on the targets placement in respect to the flame as well as the flames geometry. [9] Further on the view factor is calculated differently depending on the geometry of the surface which emits radiation. When calculating the view factor for a jet flame the emitting body can either be considered to be a cylinder or projected as a rectangular plane. If a cylindrical surface is assumed the following equation will be utilized if the target is assumed to be at ground level and with a **vertical** surface (θ=0) [10].

$$F_{v,a} = \frac{1}{\pi H} * \arctan\left[\left(\frac{L^2}{H^2-1}\right)^{1/2}\right] + \frac{L(X-2H)}{\pi H\sqrt{XY}} * \arctan\left[\left(\frac{(H-1)X}{(H+1)Y}\right)^{1/2}\right] - \frac{L}{\pi H} * \arctan\left[\left(\frac{H-1}{H+1}\right)^{1/2}\right]$$

(9)

where L=h/r, H=x/r, X=(1+H)²+L² and Y=(1-H)²+L². [10] See Figure 4 below for descriptive information about h, x, θ and r.

Alternative equation 10 can also be used [9].

$$F_{v,b} = \frac{1}{\pi H} * \arctan\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{L}{\pi}\left[\frac{(X-2H)}{H\sqrt{XY}} * \arctan\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right) - \frac{1}{H} * \arctan\left(\sqrt{\frac{H-1}{H+1}}\right)\right]$$
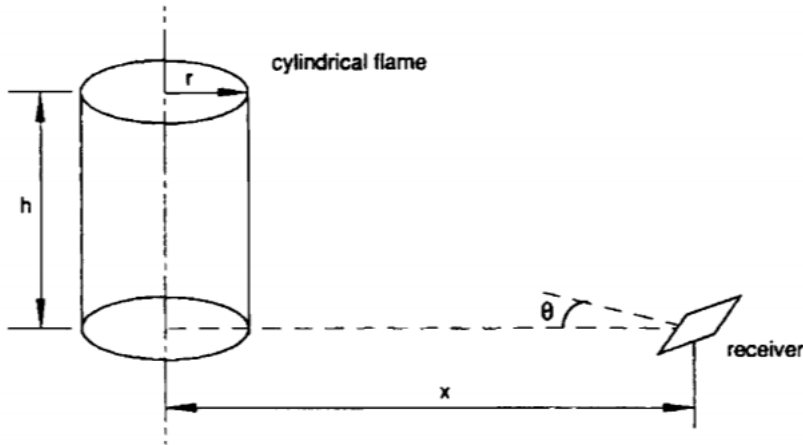
(10)

Figure 4:Illustration of a cylindrical flame and a target at floor level. Adopted from [10].

For a target with a **horizontal** surface (θ=π/2) equation 11 is utilized [10].

$$F_{h,a} = \frac{1}{\pi}\left[\arctan\left\{\left(\frac{H+1}{H-1}\right)^{1/2}\right\} - \frac{H^2-1+L^2}{\sqrt{XY}} * \arctan\left\{\left(\frac{(H-1)X}{(H+1)Y}\right)^{1/2}\right\}\right]$$

(11)

An alternative equation 12 has been presented [13] that give the same result.

$$F_{h,b} = \frac{\left(B-\frac{1}{H}\right)}{\pi\sqrt{B^2-1}} * \arctan\sqrt{\frac{(B+1)(L-1)}{(B-1)(L+1)}} - \frac{\left(A-\frac{1}{H}\right)}{\pi\sqrt{A^2-1}} * \arctan\sqrt{\frac{(A+1)(L-1)}{(A-1)(L+1)}}$$

(12)

Here L=h/r, A= (x²+H²+1)/(2*H), B=(1+H²)/(2*H) [13].

The maximum view factor, i.e. when the target is angled so it receives the most possible amount of radiation, can then be calculated by using the equation below, [10, 13,14].

$$F_{2-d1,max} = \sqrt{F_h^2 + F_v^2}$$

(13)

If a rectangular surface is assumed the view factor can be calculated by utilizing equation 14 that requires that the target is parallel to the plane, see Figure 5a [9].

$$F_{2-d1} = \frac{1}{2\pi} * \left(\frac{X}{\sqrt{1+X^2}} * \tan^{-1}\left(\frac{Y}{1+X^2}\right) + \frac{Y}{\sqrt{1+Y^2}} * \tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right)$$

(14)

where X=a/c and Y=b/c [9]. See Figure 5a below for definition of a, b and c.

However, this approach only applies when z=0 and investigating a point source, as it under other conditions exceeds 1 which is not possible.
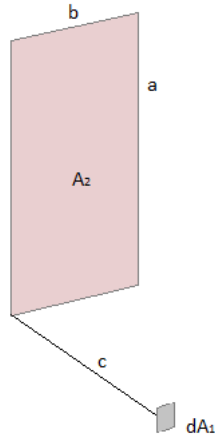

Figure 5a: Illustration of a rectangular flame and a vertical target at floor level
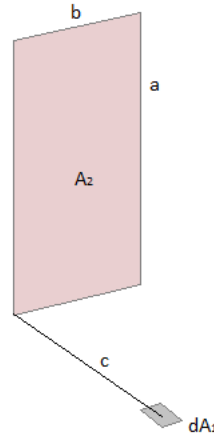
Figure 5b: Illustration of a rectangular flame and a horizontal target at floor level

If the target is horizontal (Figure 5b) equation 15 will be utilized instead [9].

$$F_{2-d1} = \frac{1}{2\pi} * \left(\tan^{-1}\left(\frac{b}{c}\right) - \frac{c}{\sqrt{a^2+c^2}} * \tan^{-1}\left(\frac{b}{\sqrt{a^2+c^2}}\right)\right)$$

(15)

where, as earlier mentioned, X=a/c and Y=b/c [9].

Depending on where in the vertical plane the target is found in relation to the flame some modifications must be made. The mentioned equations for calculating the view factor is used when the target is found at floor level, i.e. where z=0 [9,10,13,14]. If the target is placed at z≠0 this must be taken in consideration. The common method is to divide the flame and calculate the view factor for each part separately and then adding the values. Figure 6 illustrate when a target is positioned at a point z≠0. First the view factor for the part h_1 needs to be calculated as well as for the part h_2 separately. The two calculated view factors are than added to generate the total view factor for the entire flame. [9] According to Fleury, Spearpoint and Fleischmann [13] this method does not however apply for horizontal objects since the target only will receive thermal radiation from one of the two cylinders, i.e. only one side of the target are exposed.
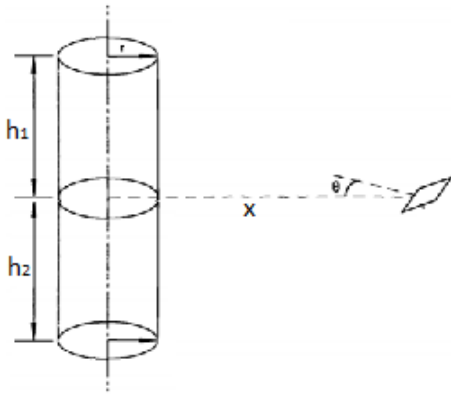

Figure 6: Illustrating a cylindrical flame and a target above floor level and $h_2 < h_2+h_1$

When the view factor is determined the incident radiation can be calculated. The view factor is denoted F_{2-d1} (respectively F_{d1-2} depending on which area that emits the radiation) in the expression for the incident radiation, q_{inc}, which is presented below [9].

$$\dot{q}_{inc,2-d1} = A_2 * F_{2-d1} * \varepsilon_2 \sigma T_2^4 \qquad (16)$$

where ε_2 is the emissivity of the surface which emits the radiation, here being a flame. Emissivity is defined as the ratio of the energy radiated from the source relative to the blackbody radiation of the same temperature [20]. The emissivity will thus adopt a value between 0 and 1. For a radiation source such as a flame, where the temperature is assumed to be the same in the centre and at the surface, the radiation ratio is expected to be the same in the centre and the surface. Thus, the surface emissivity is set equal to the flame emissivity. For this reason, ε_f is here used as ε_2. Further, σ is Stefan-Boltzmann constant (5.67*10^{-8} Wm^{-2}K^{-4}), A_2 is the area of the radiation source which here is the flame and T$_2$ is in this case equal to T_f expressed in Kelvin. The flame emissivity can be determined by utilizing equation 18 below if the emitted heat flux, $\dot{q}''_{emi}$ [kW m^{-2}] is known. The emitted heat flux is also referred to as the surface emissivity power by other authors. In some publications the expression is based on the flame properties (ε_f and T_f) and in some on the surface properties (ε_s and T_s). This also indicates that the values of the flame and surface emissivity is equal if the source is assumed to have a uniform temperature. [5, 9, 15, 16]

$$\dot{q}''_{emi} = \varepsilon_f \sigma T_f^4 = \varepsilon_s \sigma T_s^4 \qquad (17)$$

By utilizing equation 17 in equation 16 a new expression for $\dot{q}_{inc}$ based on the emitted heat flux $\dot{q}_{emi}$ is developed, see equation 18.

$$\dot{q}_{inc,2-d1} = A_2 * F_{2-d1} * \dot{q}''_{emi,2} \qquad (18)$$

No conclusive solution to compute the emitted heat flux is given in the literature, instead several alternative equations has been reported that are discussed below. Multiple expressions for the emitted heat as linear equation depending on the flame height, L [m], have been proposed by various authors and presented in an earlier study by Gomez-Mares et. al. [5].

Sonju and Hustad:

$$\dot{q}''_{emi} = 10 + 7.8L \tag{19}$$

McCaffery:

$$\dot{q}''_{emi} = 26 + 1.3L \tag{20}$$

Gómez-Mares et al.:

$$\dot{q}''_{emi} = 22 + 10L \tag{21}$$

In all three equations $\dot{q}''_{emi}$ is computed in kWm^{-2}. Even though the scattering is significant in the results from the experiments, which the relationships above is based on, the trend can be satisfactory represented by equation 21 according to Gómez-Mares et. al. [5]. The variation in the presented expressions for $\dot{q}''_{emi}$ above can be explained by the various exit velocities used in the different studies. Equation 21 is based on experiments where sonic jet flames where studied, thus this equation will be used when calculating $\dot{q}''_{emi}$ as a linear function of L in this study. However, these expressions are not accurate since $\dot{q}''_{emi}$ is positive even when L=0, which means no flame exist, thus $\dot{q}''_{emi} \neq 0$ is not true. [5] The emitted heat flux was found to increase with the mass flow rate. Figure 7 below shows the relation between the $\dot{q}''_{emi}$ and the mass flow rate which was found in the publication Experimental Thermal and Fluid Science [5]. In Experimental Thermal and Fluid Science they used E as indication for the radiation emitted from a specific source instead of $\dot{q}''_{emi}$. The relationship was found to be described by equation 22 (also shown in Figure 7). [5]
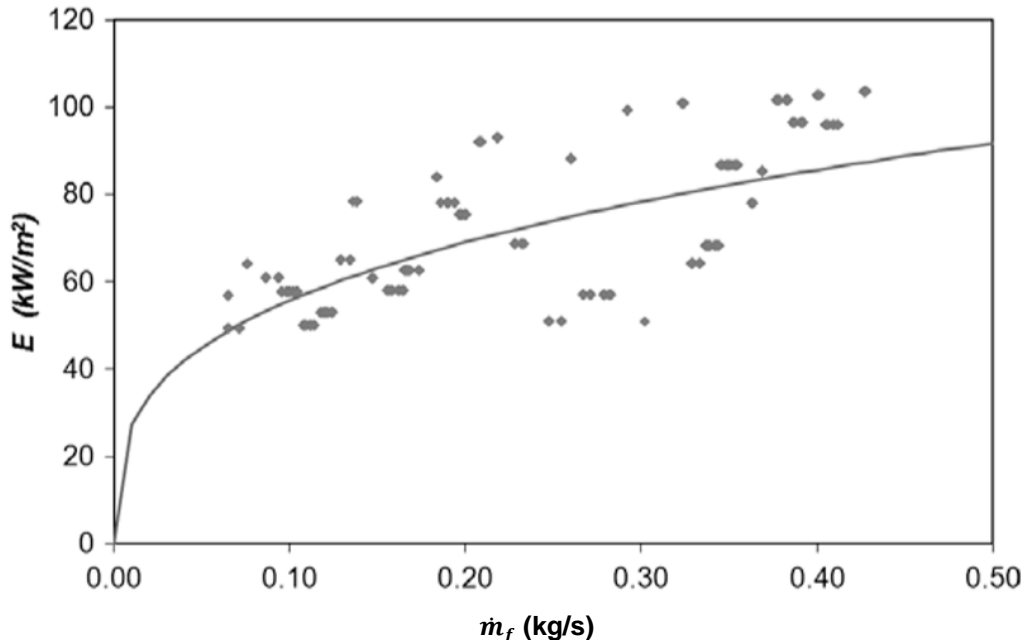

Figure 7: The relation between the flame surface emissive power and the mass flow rate based on a propane flame. Graph adopted from [5]

$$\dot{q}''_{emi} = 113.7 * \dot{m}_f{}^{0.31} \tag{22}$$

Where $\dot{q}''_{emi}$ here is used instead of E to denote the emitted heat flux.

Alternative equations for calculating the $\dot{q}''_{emi}$ has been presented in various publications [5, 16, 18]. The following equation 23 shows an alternative expression for calculating $\dot{q}''_{emi}$, which was derivative from experiments preformed where jet flames where studied [5].

$$\dot{q}''_{emi} = 25.7 * L^{0.65} \qquad (23)$$

Further, expressions of the emitted heat flux, $\dot{q}''_{emi}$, have been found were the fraction of the total amount of heat which is released as radiation is considered, φ_s. Xu et. al. presented the following expression (equation 24) as a suggestion for calculating $\dot{q}''_{emi}$ for jet flames, [18]

$$\dot{q}''_{emi} = \frac{\varphi_s \dot{m} \Delta H_c}{A_f} \qquad (24)$$

A corresponding expression is presented by Gomez-Mares et. al. [5] (equation 25).

$$\dot{q}''_{emi} = \frac{\varphi_s \dot{q}}{A_f} \qquad (25)$$

Furthermore, $\dot{q}''_{emi}$ can be determined by using equation 26 [16]. Here the area of a sphere is used instead of the area of the specific flame studied. Thus, this equation can be considered to be suitable for point source calculations or for flames with such geometric features that they can be considered to be spherical.

$$\dot{q}''_{emi} = \frac{\varphi_s \dot{q}}{4\pi r^2} \qquad (26)$$

To solve equation 24-26, the fraction of heat radiated from the surface of the flame, φ_s, must be determined. φ_s is and depends on the gas velocity, u_j. φ_s is according to Selma E. et. al. [17] calculated by utilizing equation 27 below,

$$\varphi_s = 0.21 e^{-0.00323 u_j} + 0.11 \qquad (27)$$

Determining the safety distance

To determine at what closest distance from a jet flame combustible material is acceptable, the relationship between the incident radiation and the distance as a function of the view factor is applied. As noted earlier is the maximum accepted temperature increase above ambient temperature for combustion material from a jet flame 47.2 °C according to NFPA 160, giving T_{AST} = 340.2 K when the ambient temperature is 20 °C (293 K). The maximum accepted radiation temperature, T_r, can then be calculated by utilizing expression 28 where the input variables for the different temperatures is expressed in Kelvin [9].

$$\varepsilon_s \sigma (T_r^4 - T_{AST}^4) + h_c (T_g - T_{AST}) = 0 \qquad (28)$$

where h_c is the heat convection coefficient, ε_s is the surface emissivity and here T_{AST}=340.2 K and T_g = 293 K. The heat convection coefficient depends on the surface temperature and the gas temperature as well as the angle of the surface, e.g. here a vertical or horizontal target. If the factors mentioned above is known the heat convection coefficients can be determined according to the graphs presented in figure 6.4 and 6.5 in Temperature Calculation in Fire Safety Engineering by Wickström [9]. Setting the surface temperature equal to T_{AST}=47.2 °C (340.2 K) and T_g=20 °C (293 K), $h_{C,V}$ is determined to 7.5 W/m²K and $h_{C,H}$ is determined to 6 W/m²K . To compute the largest safety distance independent on the material of the target the maximum possible emissivity will be used. The surface emissivity (ε_s) will hence be set to 1 due to that the material of the target is unspecified in this study.

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Further on, when the radiation temperature is determined the maximum accepted incident radiation can be calculated by equation 29 [9].

$$\dot{q}''_{inc} \equiv \sigma T_r^4 \qquad (29)$$

The maximum accepted view factor can be calculated through the relation between the incident radiation and the emitting heat flux which can be expressed as follows by utilizing equation 18.

$$\frac{\dot{q}''_{inc}}{\dot{q}''_{emi}} = F_{2-d1} \qquad (30)$$

By comparing the value of the maximum accepted view factor calculated by using equation 30 to the calculated view factors for each point separately, a minimum acceptable distance can be determined.

Results

Calculations

Energy release rate and flame temperature

Assuming a linear increase of the mass flow rate in relation to the flame height according to Figure 2 the mass flow for a flame of 25 metres will be 3.27 kg/s and 1.8 kg/s for a flame of 15 metres with an orifice diameter of 12.75 mm as illustrated in Figure 8, adapted from Figure 2.The observations of Figure 2 are based on significant smaller jet flames and thus the extrapolation to 15 and 25 m will generate some uncertainties. Among other things, the assumption of a linear function is made. The lack of reports from experiments with larger flames makes this extrapolation needed to apply the computations of this study. Since each line in Figure 2 is linear, after a certain point, this shows a clear and reliable trend for the relationship between the flame height and mass flow rate for jet flames. Even though the experimental data is for small jet flames, the extrapolated values is thus based on a function determinate by the experimental data which generates a reliable result with the statistic uncertainties in consideration.
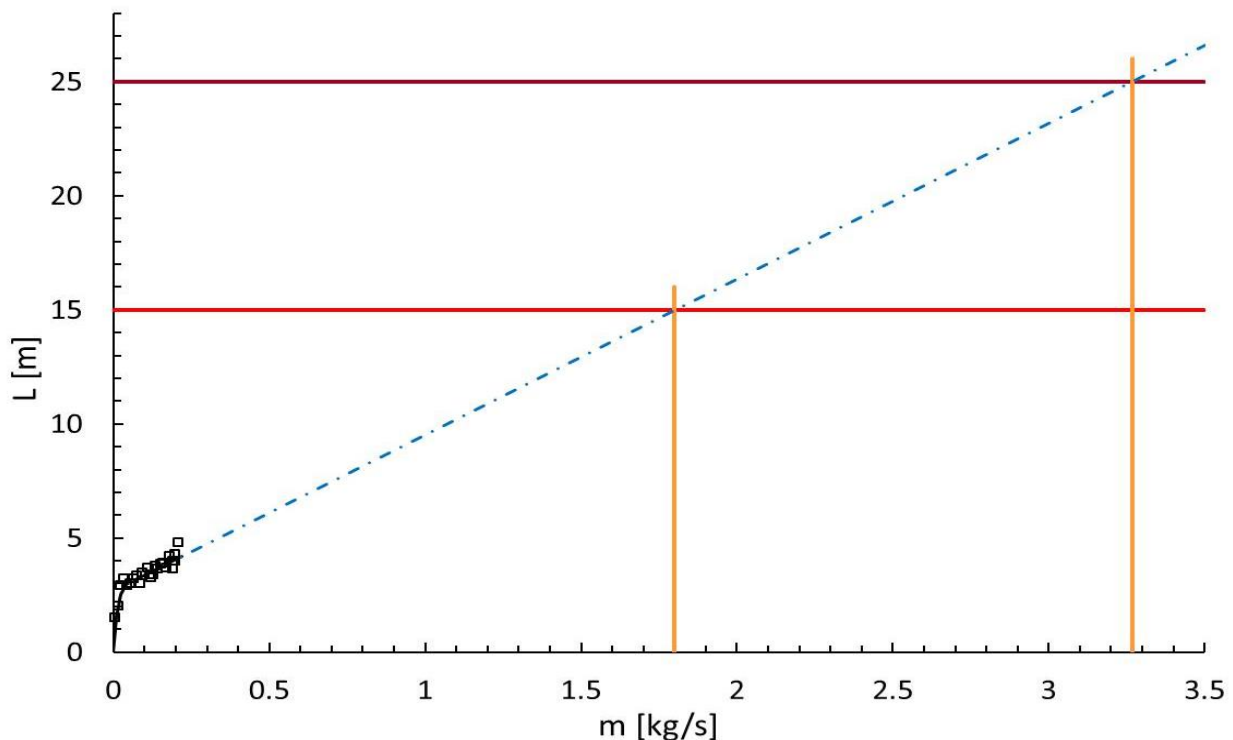

Figure 8: The mass flow as a function of the flame height for jet flames with a flame height of 15 respectively 25 meters. Adopted from figure 2 from [1]

Multiple calculations have been made for the energy release rate and the flame temperature by utilizing various calculation methods. Since it was not possible to measure the gas flux and composition in an experiment within this study a theoretical approach is used.

The total amount of oxygen utilized during complete combustion according to the reaction formula for the specific amount of fuel for respective jet flame is computed. As Isopar L is a mixture of hydrocarbons having 11 to 13 C atoms, Dodecane is used as a proxy in the following applications. This due to its similarity in chemical structure to Isopar L, since Dodecan is a straight hydrocarbon chain including 12 C atoms. The reaction formula for complete combustion of Dodecane is:

$$2\,C_{12}H_{26}\,(l)\ +\ 37\,O_2\,(g)\ \rightarrow\ 26\,H_2O\,(g)\ +\ 24\,CO_2\,(g) \tag{i}$$
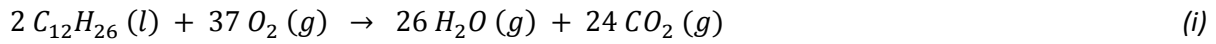
According to Figure 8 the mass flow of fuel for a 15 meters high jet flame is 1.69 kg/s and for a 25 meters high jet flame it is 3.02 kg/s. The molar mass for respective component in the reaction formula where determined, and thereafter their mass per reaction where calculated. The amount of oxygen corresponding to the amount of fuel is finally calculated. In Table 1 are the calculated values presented, giving the total amount of oxygen utilized per reaction.

Table 1: The calculated amount of oxygen, water and carbon dioxide per unit fuel, Dodecane

Substances	Molar mass [g/mol]	Mass per reaction (i) [g]	Mass per kg $C_{12}H_{26}$ [kg]
$C_{12}H_{26}$ (l)	170	340	1.0
O_2 (g)	32	1184	3.5
H_2O (g)	18	468	1.4
CO_2 (g)	44	1056	3.1

By using the correlation shown above between the amount of fuel and oxygen that reacts, the total amount of oxygen for a 15-meter jet flame is determined to 6.27 kg/s and 11.4 kg/s for a 25 meters jet flame. Multiplied with the amount of energy released per kilogram oxygen reacting, the energy release rate is determined to 82 MW respectively 149 MW according to calculations with equation 2. Equation 8 is thereafter utilized to determine the flame temperature, with the constants n and K set to 0.5 and 6.8 respectively since assumption is made that each studied point is within the continuous region. Thus, this shows that the energy release rate has no effect on the temperature. The temperature for a jet flame of 15 meters as well as 25 meters is calculated to be 872 $^\circ$C in an environment of 20 $^\circ$C. Since the energy release rate has no influence the calculated flame temperature was the same independent in which way the energy release rate was calculated and the result, see the two following sections.

Further, calculations where made where the relationship between the energy release rate and the heat of combustion where utilized (see equation 5). The heat of combustion for Isopar L is assumed to be equal to the heat of combustion for Dodecan, 44.2 MJ/kg [8], due to its similarity in chemical structure. Due to its similarity in chemical structure, a similar amount of energy is assumed to be released during combustion of Isopar L as from Dodecan. χ is assumed to be 0.7 since the Isopar L is a relatively sooty fuel. $\dot{q}$ was found to be constant within the entire flame. For a 15-meter high flame $\dot{q}$ is calculated to be 55.7 MW and for a 25-meter flame to 101 MW.

Finally, the flame temperature where calculated by using the relationship between the flame height and the energy release rate which is presented in Experimental Thermal and Fluid Science by M. Gomez-Mares et. al. [5] Solving equation 5 for $\dot{q}$ resulted in $\dot{q}$=108 MW for a jet flame with a flame height of 15 meters and $\dot{q}$=313 MW for a flame height of 25 meters. Figure 9 shows how the energy release rate changes with the flame height.
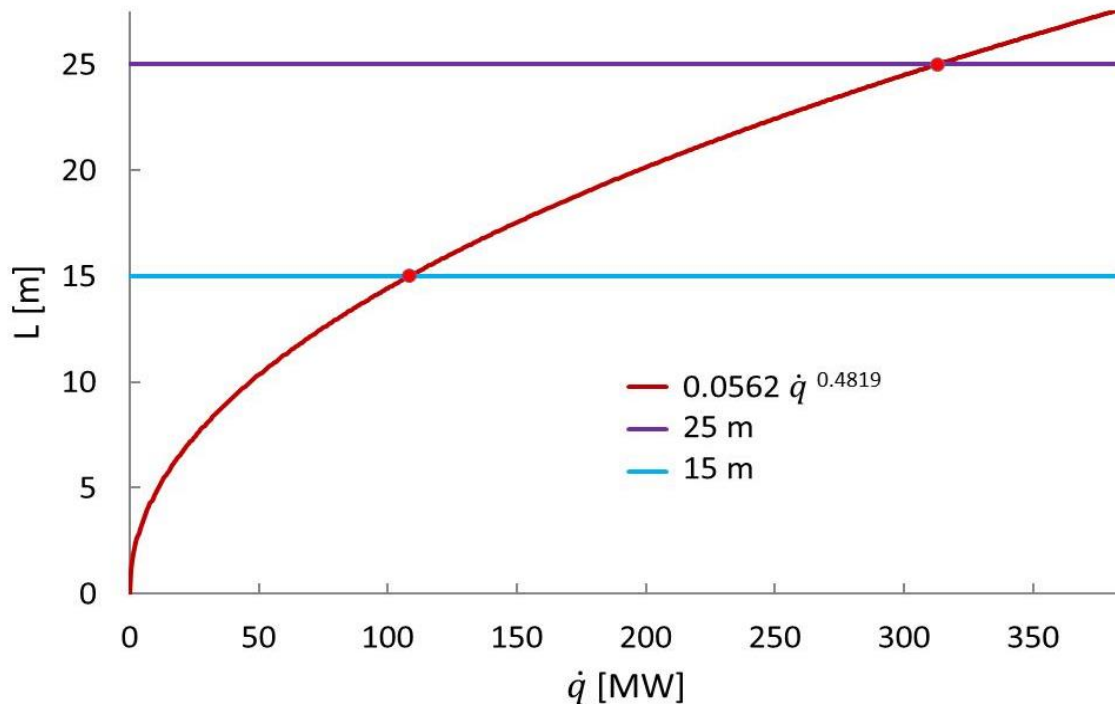
Figure 9: The energy release rate as a function of the flame height, equation 5, for jet flames with a flame height of 15 respectively 25 meters

Every calculation method used to determine the energy release rate has generated various results (see Table 2 and Table 3). However, the different calculation procedures have all resulted in the same flame temperature, 872 °C. As mentioned, this is expected since the energy release rate has no influence when calculations are made for the continuous region with equation 8. The variation of the energy release rate indicates however that the computations utilizing equation 2, 4 and 5 are unreliable. Further, the calculated temperature of 872 °C is assumed to be low for a flame of such magnitude as the jet flames studied in this case. This raises questions about the hypothesis that equation 8 can be applied for calculations concerning jet flames. Further calculations are thereby based on the assumed flame temperature of 1200 °C, which is concluded to be in the high range of the various temperatures that jet flames reaches based on values from previous experiments [7, 21, 22], to ensure that the end result will be on the safe side.

Table 2: Calculated energy release rate for a 15 meter jet flame

Equation	Energy release, $\dot{q}$ [W]
O_2 *(eq 2)*	$82.1*10^6$
LQ *(eq 6)*	$108*10^6$
H_c *(eq 5)*	$55.7*10^6$

Table 3: Calculated energy release rate for a 25 meter jet flame

Equation	Energy release, $\dot{q}$ [W]
O_2 *(eq 2)*	$149*10^6$
LQ *(eq 6)*	$313*10^6$
H_c *(eq 5)*	$101*10^6$

View factor

The view factor depending on the distance and height were calculated. Below calculations for both rectangular and cylindrical radiation sources with variable sizes are presented for one horizontal and one vertical target, respectively. Computations of the view factor for a cylindrical radiation source and a vertical target were made using two different equations 9-10 to ensure the result were reliable. Two different approaches (equation 11-12) were also utilized for calculations for a horizontal target and a cylindrical flame. The two equations for each individual target were identical, and when compared to predefined table values in former studies the values also agreed [10]. Comparison of the view factor for a vertical and a horizontal target is plotted as a function of the distance to the flame. For targets placed at floor level the view factor for an angled target is also compared. Figure 12 shows the view factors for vertical, horizontal and angled targets at floor level (z=0) for a jet flame of 15 meters. Figure 11 shows the corresponding graphs for a jet flame of 25 meters.
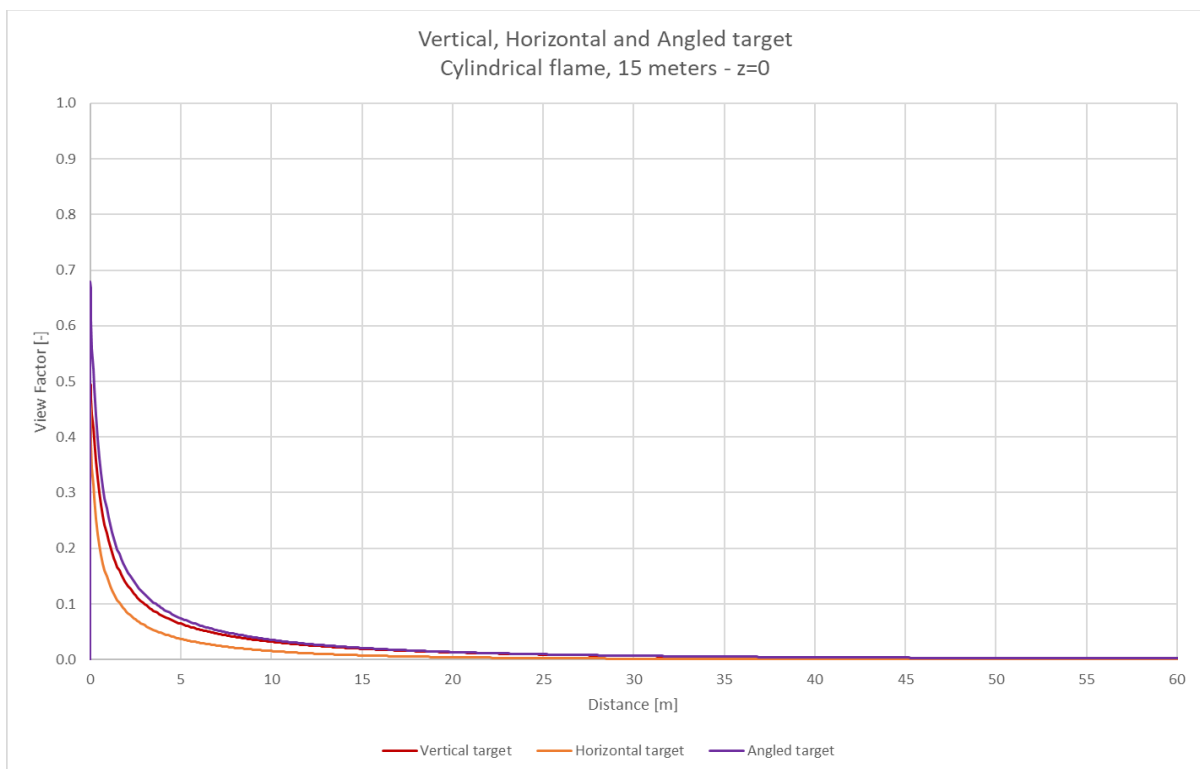
Figure 10: View factor, cylindrical flame, 15 meters at z=0. The red line represents the view factor for a vertical target, the orange for a horizontal target and the purple for an angled target in such way that the maximum amount of radiation reaches the target.
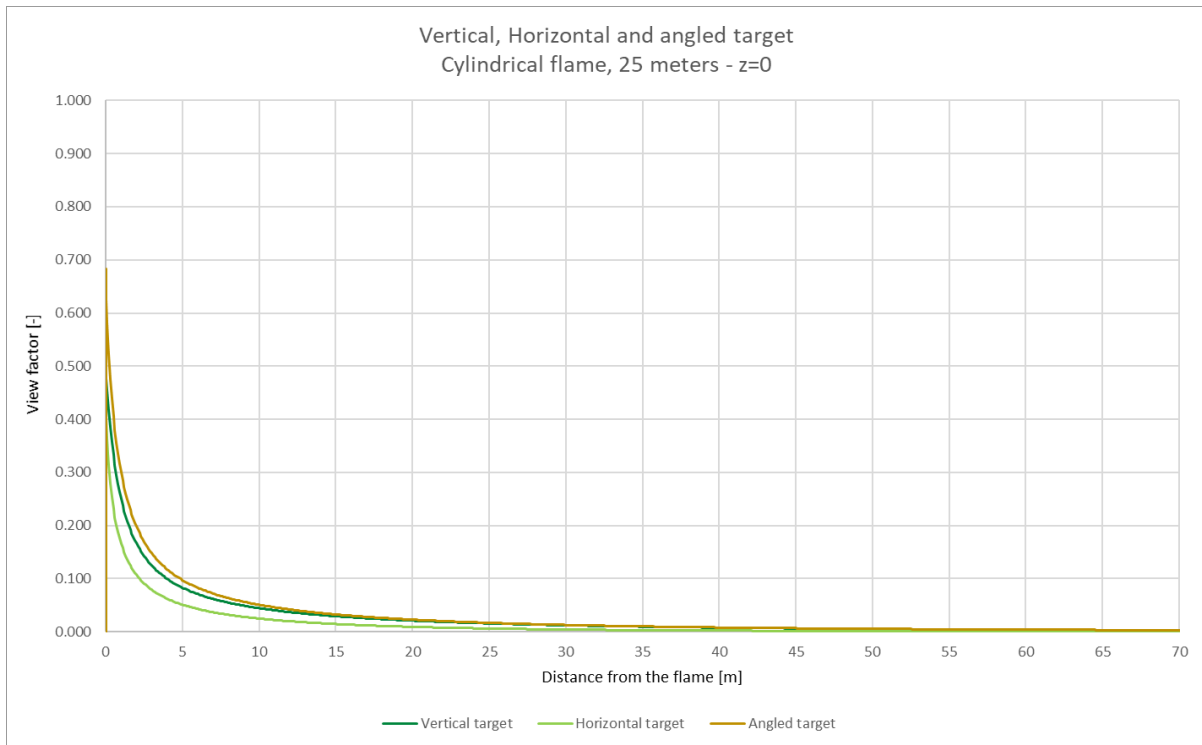
Figure 11: View factor, cylindrical flame, 25 meters at z=0. The dark green line represents the view factor for a vertical target, the light green for a horizontal target and the yellow for an angled target in such way that the maximum amount of radiation reaches the target.

For both flame sizes, the graphs above show that the view factor is smallest for a horizontal target and gives the highest value for an angled target.

Further, view factors were calculated for various height of the targets in relation to the flame, increasing by one meter between each case. Below are the view factors for a vertical and a horizontal target, respectively, located in the middle of each flame presented. Figure 12 represents a jet flame of 15 meters and Figure 13 a jet flame of 25 meters. The figures illustrate the variation of the view factor with distance from the flame when both the upper and lower parts of the cylindrical radiation source are considered for vertical target. For the horizontal target only the upper or lower part of the radiation source, the one that is largest, is considered when determining the view factor.
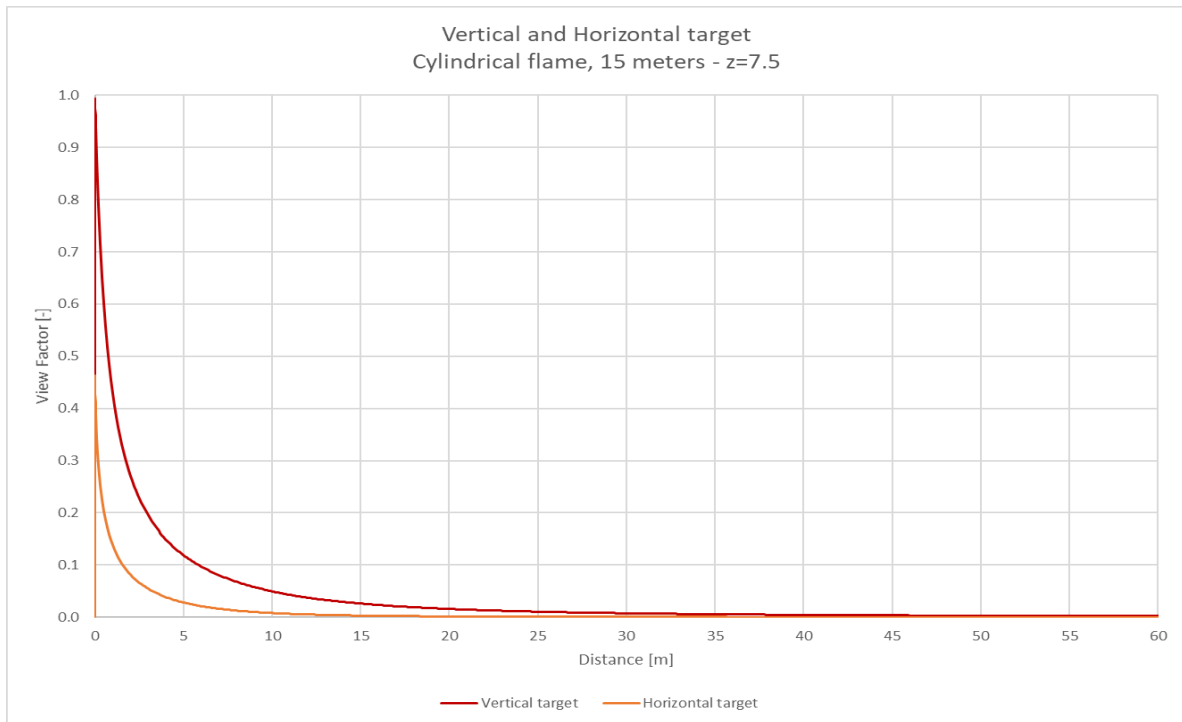
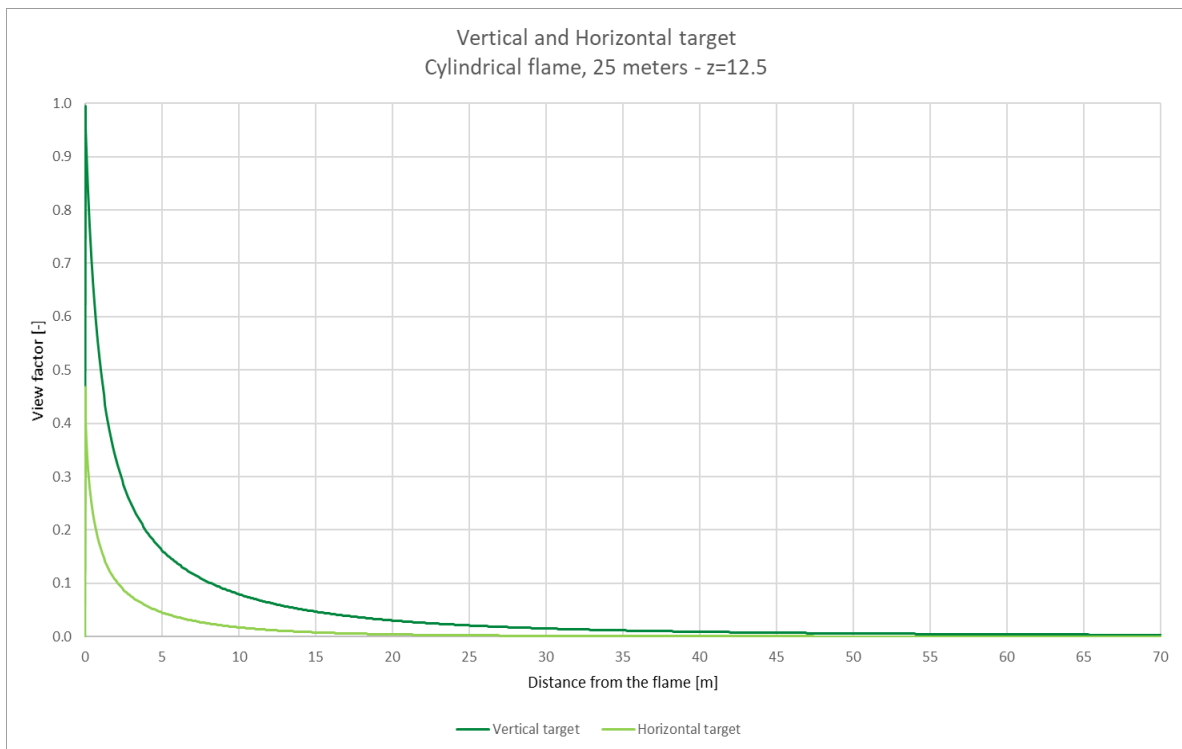*Figure 12: View factor for a vertical and horizontal target. Cylindrical flame of 15 meters at z=7.5*

Figure 13: View factor for a vertical and horizontal target. Cylindrical flame of 25 meters at z=12.5

It is shown that the view factor for a horizontal target is smaller also in the middle of the flame, the view factor for the vertical flame is in between.

The variation of the view factor due to the height above the ground level to the target is shown in Figure 14 and Figure 15 below for a jet flame of 15 respectively 25 meters. Each line in each graph

represents a different height of the target. Since vertical targets generate the highest view factors these will determine the safety distance. Therefore, only the figures showing the variation of the view factor in relation to the height for vertical target is presented below.
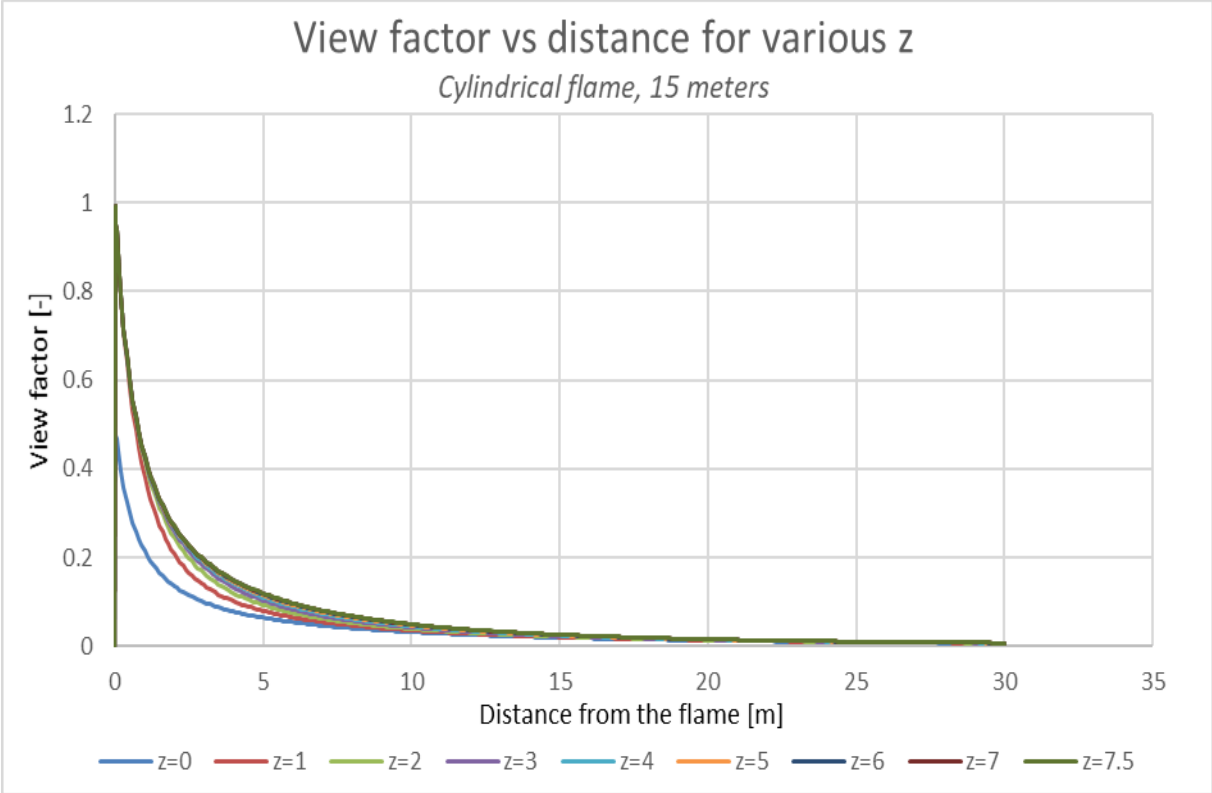

Figure 14: View factor for vertical targets and a cylindrical flame of 15 meters for various heights, z
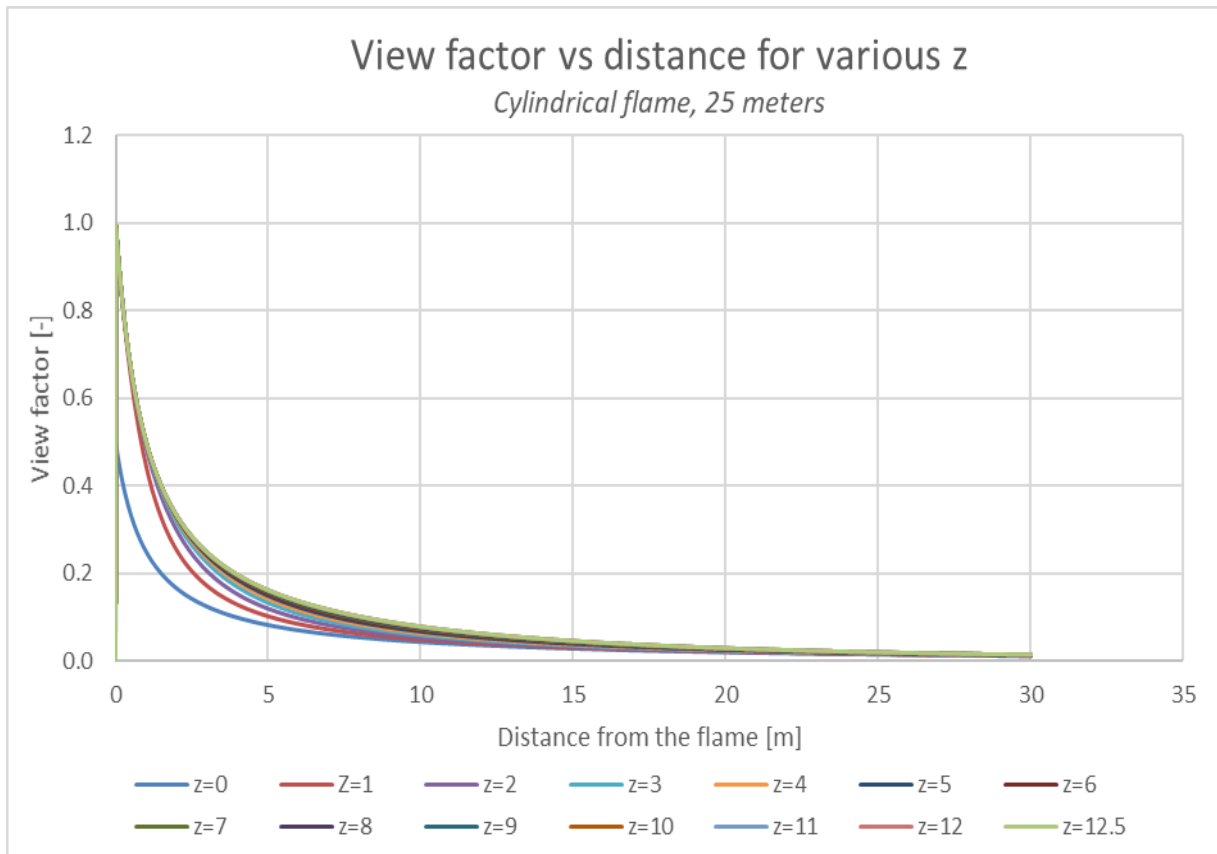
Figure 15: View factor for a vertical target and a cylindrical flame of 25 meters at various heights, z

Figure 14 and 15 shows that the view factor at the bottom of the flame (z=0) is the same as in Figure 12 and 13, while it increases significantly when the target is at z>0.The trend is similar when the target is placed above floor level as seen when placed at z=0, with decreasing values of the view factor with distance from the flame. The explanation of the lower values at z=0 is that only half of the target faces the flame, while half is below the flame.

The corresponding calculations were made for rectangular radiation sources for vertical objects and compared to the results for cylindrical flames (see Figure 16-19). If the results were the same one could compute the view factors for cylindrical flames with the more straight forward equation for the rectangular flame. However, as expanded below this is not the fact.
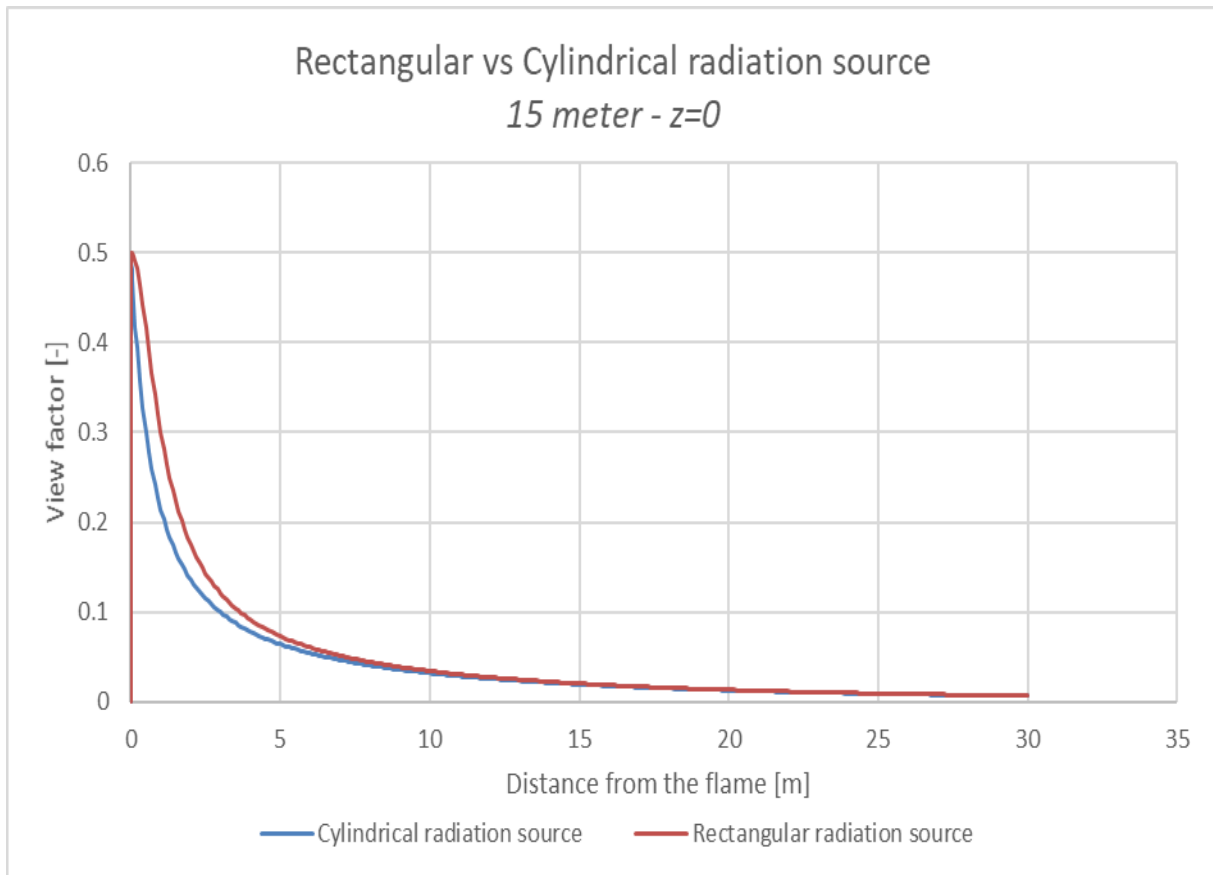
Figure 16: View factor vs distance at z=0 for a 15 meter high cylindrical flame respective a rectangular for a vertical target.
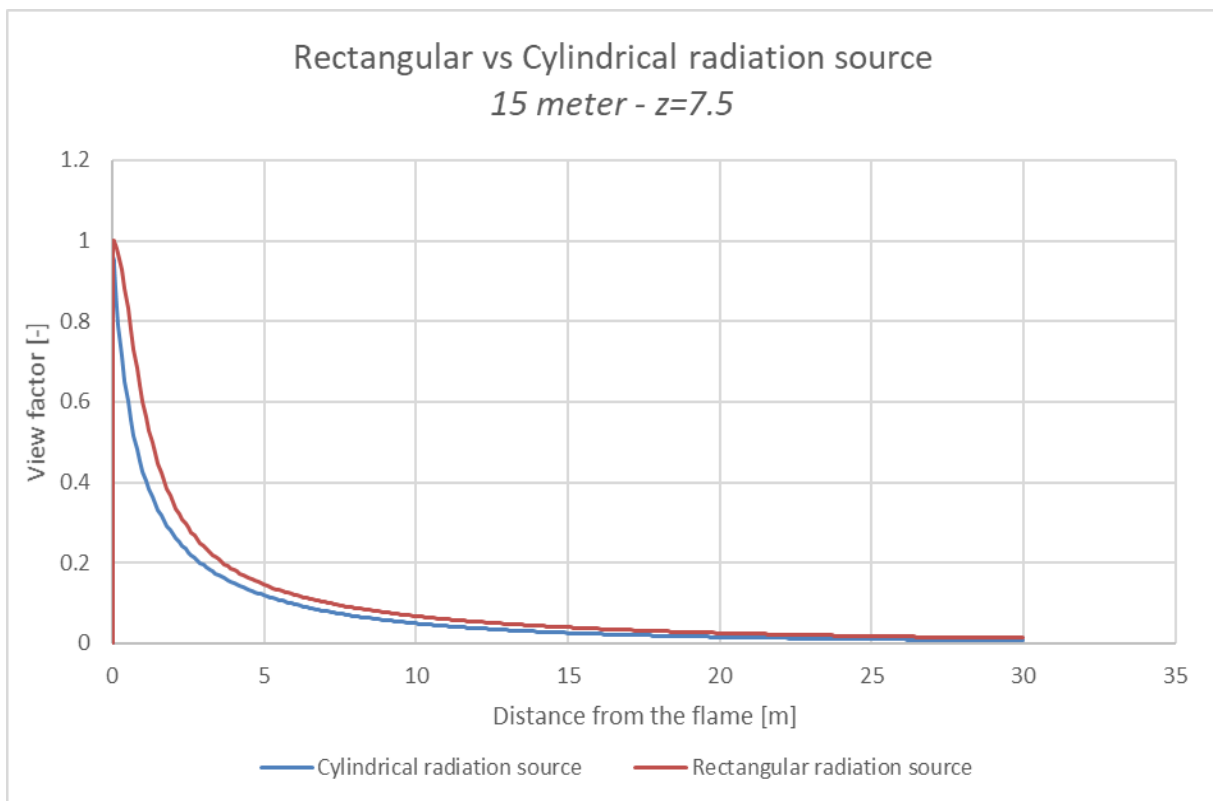

Figure 17: View factor vs distance at z=7.5 for a 15 meter high cylindrical flame respective a rectangular for a vertical target.
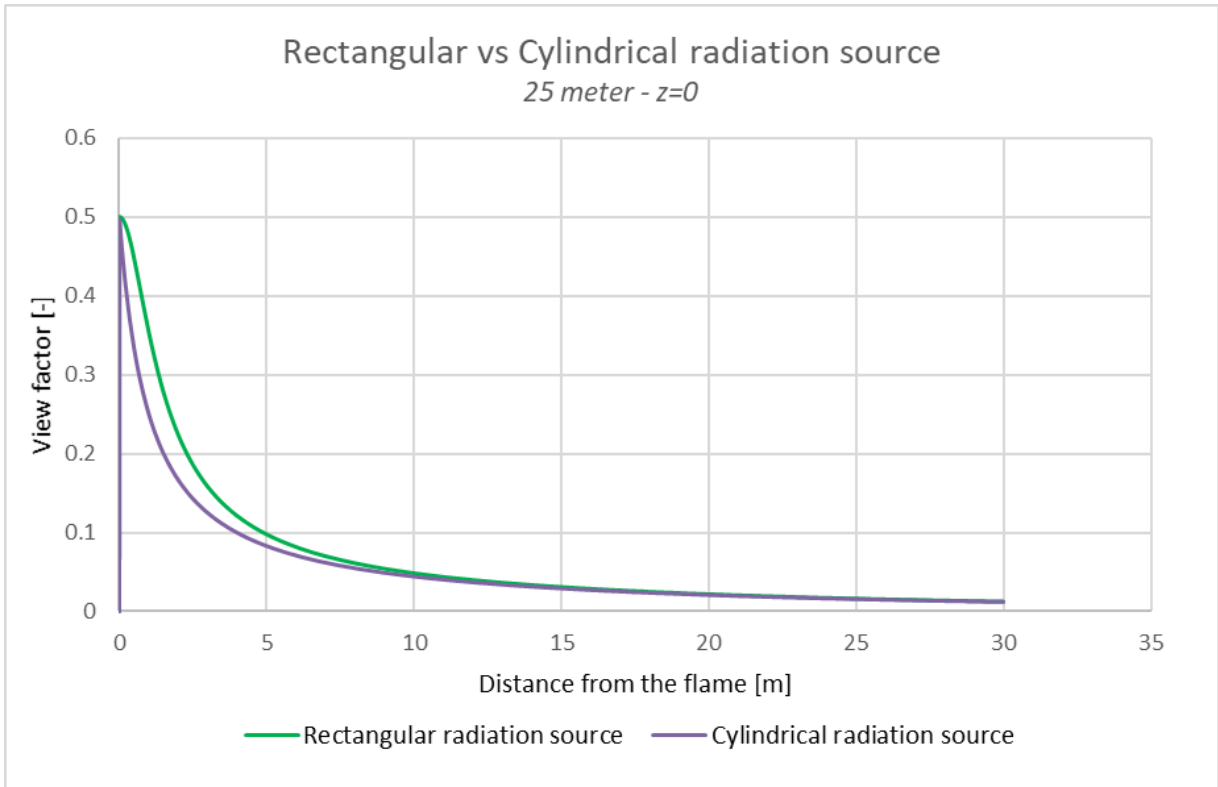
Figure 18: View factor vs distance at z=0 for a 25 meter high cylindrical flame respective a rectangular for a vertical target.
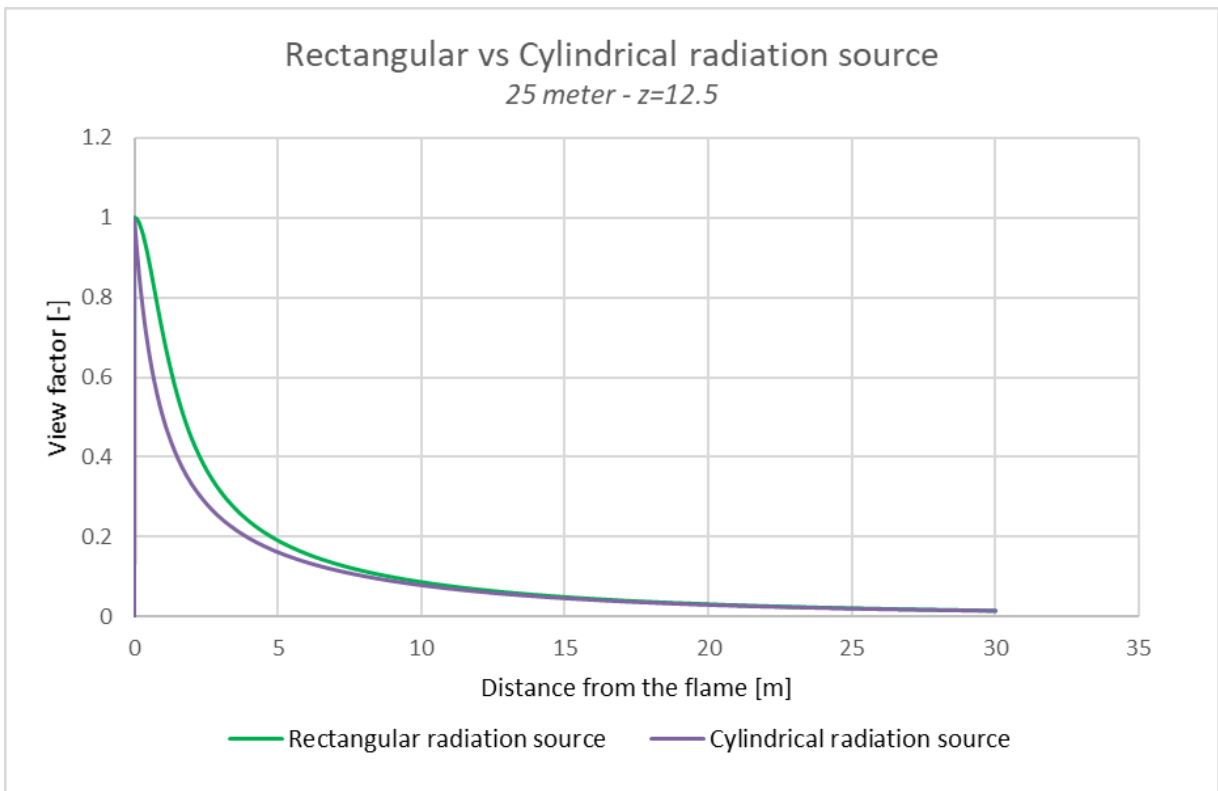

Figure 19: View factor vs distance at z=12.5 for a 25 meter high cylindrical flame respective a rectangular for a vertical target.

As seen in the figures 16-19 above the view factor decreases more rapidly for a cylindrical radiation source compared to a rectangular independent of the flame height and the vertical level of the target. Thus, the difference reduces with the distance from the flame in each case. However, the difference in the value of the view factor is of such magnitude that it cannot be recommended to calculate the view factor using the equation adopted for a rectangular radiation source if the real flame can be considered to be cylindrical.

Determination of the safety distances based on acceptable view factors

The upper limit of T_{AST} is 67.2 °C (340.2 K) in order not to exceed the maximum accepted temperature for combustible material according to NFPA 160. Based on this requirement of T_{AST} the maximal accepted radiation temperature, T_r, is calculated by applying equation 28. Here the surface emissivity, ε_s, is set to 1 since this will generate the lowest acceptable radiation temperature and thus the largest safety distance independent on the material of the target. The heat convection coefficient is determined to $h_{C,V}$=6 and $h_{C,H}$=7.5 for the surface temperature 340.2 K and the gas temperature 293 K, respectively. When inserting the values of ε_s, $h_{C,V}$, $h_{C,H}$, stated above, together with T_{AST}=340.2 K and T_g=293 K in equation 28 the maximum accepted T_r is calculated to 362 K if the target is faced towards the flame (vertical target) and 368 K for a target parallel to the floor (horizontal target).

When the accepted T_r is determined the corresponding incident radiation, $\dot{q}_{inc}$ is calculated by utilizing equation 29. For a vertical target this resulted in $\dot{q}''_{inc,V} = 976$ kW/m^2 and for a horizontal target $\dot{q}''_{inc,H} = 1040$ kW/m^2. Using equation 30 the maximum accepted view factors are then calculated by dividing $\dot{q}''_{inc}$ with $\dot{q}''_{emi}$. These calculations are made for both $\dot{q}''_{inc,V}$ and $\dot{q}''_{inc,H}$ and the different $\dot{q}''_{emi}$ achieved from equations 17and 19-26, respectively. The results are presented in Table 4, where column 2 is for a vertical target and 3 for a horizontal target, both for a flame of 15 meters, while column 4 and 5 are for vertical and horizontal targets, respectively, and a 25 m flame.

Table 4: Calculated view factors between flame and target surface based on emitted heat flux calculated in various ways

$\dot{q}''_{emi}$	$F_{2\text{-d1,15,V}}$	$F_{2\text{-d1,15,H}}$	$F_{2\text{-d1,25,V}}$	$F_{2\text{-d1,25,H}}$
$\varepsilon_f \sigma T_f^4$	0.00366	0.00390	0.00366	0.00390
$22 + 10 * L$	0.00568	0.00605	0.00359	0.00382
$113.7 * \dot{m}_f^{0.31}$	0.00716	0.00763	0.00595	0.00634
$25.7 * L^{0.65}$	0.00653	0.00696	0.00469	0.00500
$\dfrac{\varphi_s \dot{m} \Delta H_c}{A_f}$	0.00281	0.00299	0.00343	0.00366
$\dfrac{\varphi_s \dot{q}}{A_f}$	0.00272	0.00290	0.00342	0.00365
$\dfrac{\varphi_s \dot{q}}{4\pi r^2}$	0.0000272	0.0000290	0.000288	0.000307

When calculating the different values of $\dot{q}''_{emi}$, the energy release rate is set to 82.1 MW for the 15 m high flame and 149 MW for the 25 meter high flame which are the values generated when using equation 2. These values are used since this approach generated the highest value of the energy release rate, except for values calculated based on data from experiments where propane flames where studied. When utilizing equation 17 the flame emissivity is set to 1.

Table 4 shows that the values of the calculated view factors varies in every case depending on which equation for $\dot{q}''_{emi}$ used. When determine which value that will be used in further calculations the adaptability to jet flames, the fuel Isopar L and the geometry of the flame is taken in consideration. E.g. Equation 26 will not be assumed generate a reliable value of the view factor in this case. This as the flames studied in this project are cylindrical, and the margin of error is expected to be significant if the flames would be assumed to be spherical as in equation 26. Further, the result from equation 19 will not being considered since earlier publications have enlightened problems with the equation in question, such as when the flame height is equal to 0 equation 19 will still give a positive value for the heat emitted. Since equation 22 and 23 is based on values from experiments with propane jet flames the values generated from these approaches will not be utilized due to the uncertainty of applying the same equation on flames with different fuels. Equation 25 is also based on values from experiments with propane jet flames, but the possibility of adapting this equation to any other fuel is assumed if another value of $\dot{q}$ is utilized. However, equation 2 is mentioned as a general equation adapted for jet flames, and the use of the heat of combustion in this equation gives the possibility of adapting it to a specific fuel. Thereby, this equation will be used as a possible solution or alternatively equation 17. The one of these two that gives the worst-case scenario will be used. The smaller the accepted view factor is the larger the safety distance will be. Since the value of the view factor is smaller when calculations with equation 24 is made compared to equation 17 these values will be applied. Thus, the maximum accepted view factor is set to $F_{2\text{-}d1\_15,V}=0.00281$ and $F_{2\text{-}d1\_15,H}=0.00299$ for a 15 meter flame, $F_{2\text{-}d1\_25,V}=0.00343$ and $F_{2\text{-}d1\_25,H}=0.00366$ flame for a 25 meter flame as seen above in Table 4.

The maximum accepted view factors have been inserted in the plots of the calculated view factor for respective flame and target and is presented below in Figures 20-27. This enables an evaluation of the distance at which the maximum allowed radiation temperature is reached and thus also the maximum accepted adiabatic surface temperature. This occurs at the distance from the flame where the calculated view factor for each target is equal to the calculated maximal accepted view factor. The distance where the maximum acceptable adiabatic surface temperature is reach is corresponding to the required safety distance. The graphs show that the maximal accepted adiabatic surface temperature (T_{AST}) is reached at approximately 47 meters from the flame for a 15 meter high flame if the target is at floor level and angled, i.e. when the target is facing the flame in such way that the maximal possible radiation reaches the target. For a vertical target at floor level the distance is also approximately 48 meters. For a horizontal target at floor level is the accepted T_{AST} reach earlier, at approximately 23 meters from the same flame (for a target facing upwards). Corresponding for a horizontal target at a level of half the flame height for a 15 meter flame the accepted T_{AST} is reach at 15 meters. For a vertical target the distance at which the accepted T_{AST} is reached is approximately the same as at floor level, 49 meters from the flame, at mid-height. For a 25 meter flame the same T_{AST} is reach at approximately 65 meters for both an angled target and a vertical and 32 meters for a horizontal target (facing upwards) at floor level. For targets placed at a level of half the flame height the distance for a vertical target is slightly larger than at floor level, 67 meters, and for a horizontal target this distance is 22 meters.
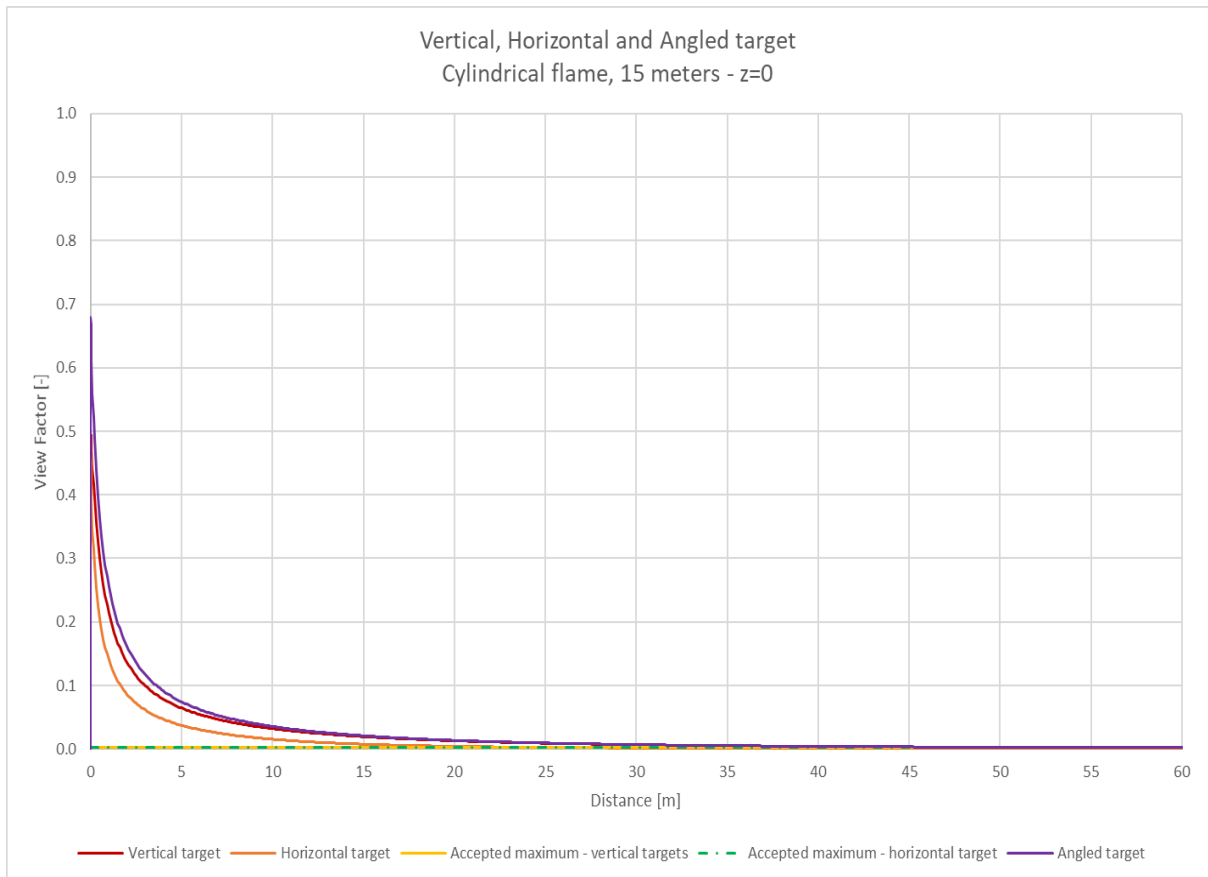
Figure 20: View factor for a vertical respective a horizontal target at floor level compared to the accepted view factor for a 15 meter high flame
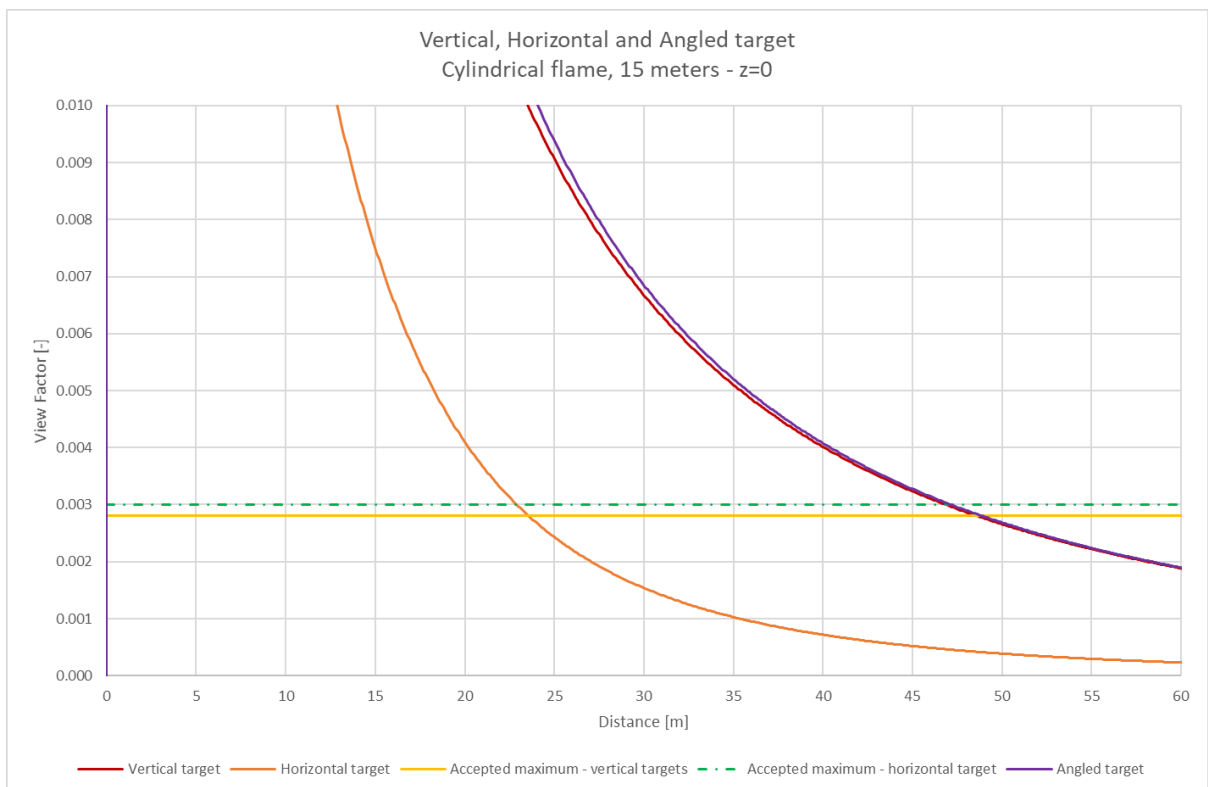

Figure 21: Expanded scale for the low values of the view factor for a vertical respective a horizontal target at floor level compared to the accepted view factor for a 15 meter high flame
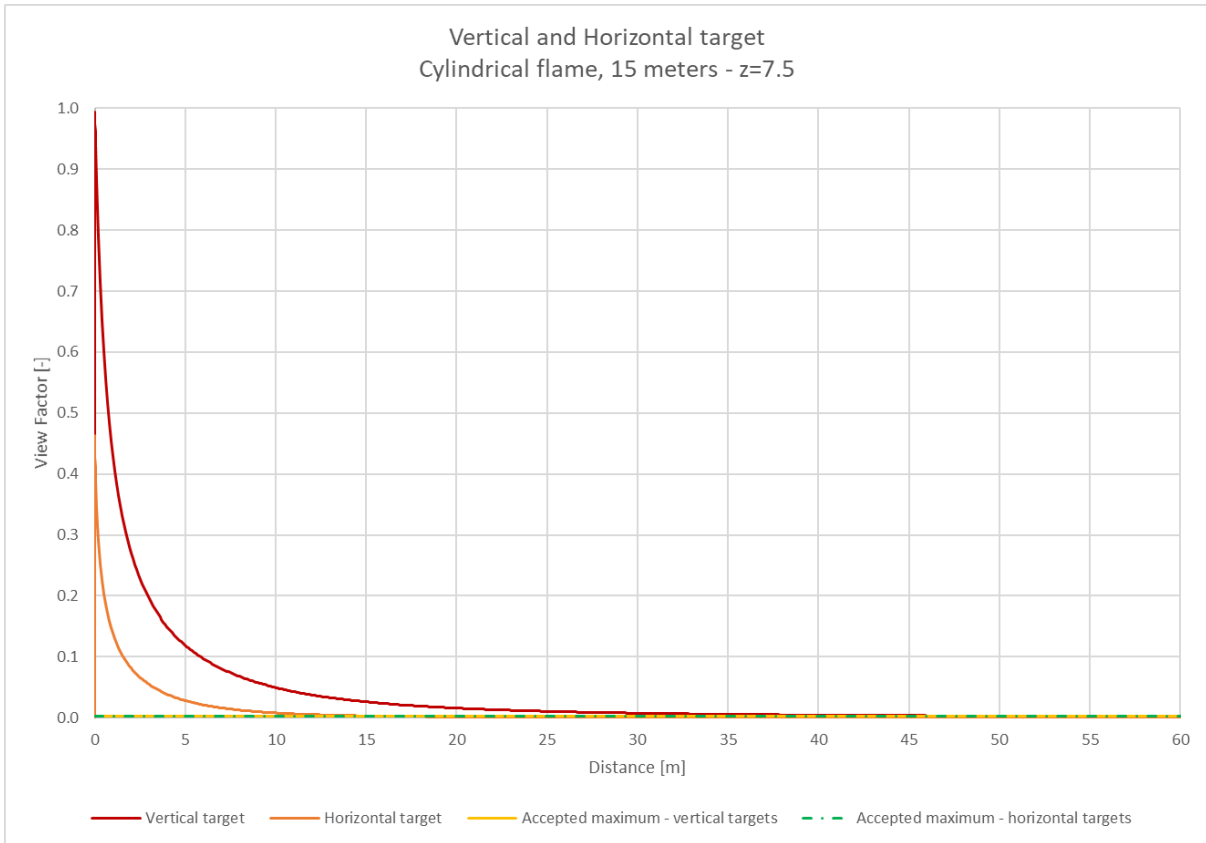
28

Figure 22: View factor for a vertical respective a horizontal target at a level of z=7.5 meter compared to the accepted view factor for a 15 meter high flame
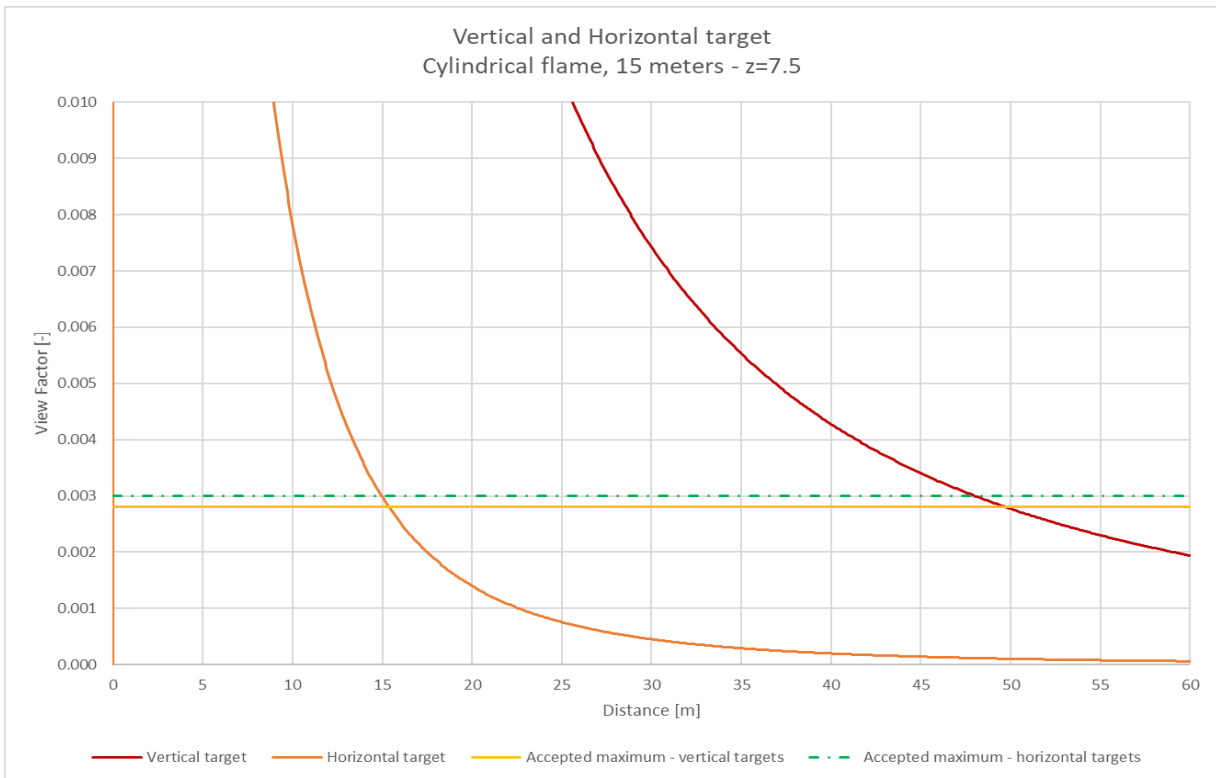

Figure 23: Expanded scale for the low values of the view factor for a vertical respective a horizontal target at a level of z=7.5 meter compared to the accepted view factor for a 15 meter high flame

29
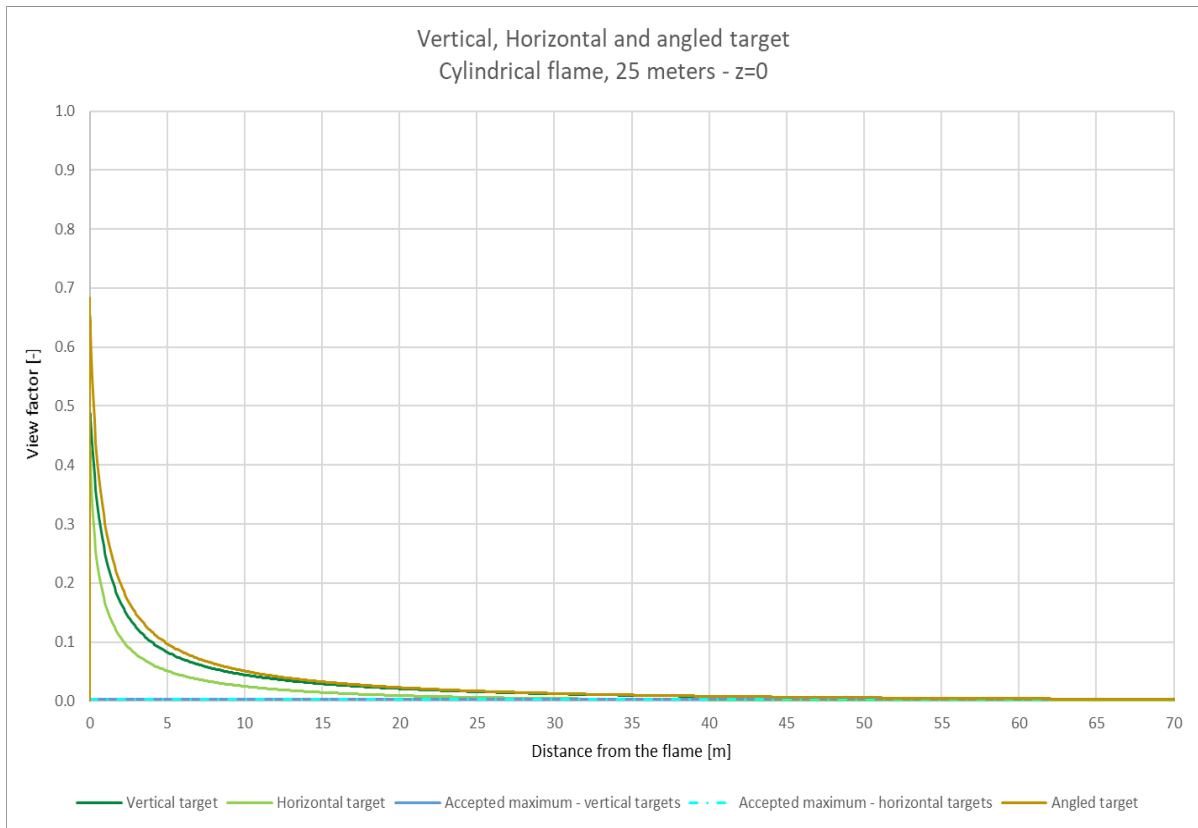
Figure 24: View factor for a vertical respective a horizontal target at floor level compared to the accepted view factor for a 25 meter high flame

Figure 25: Expanded scale for the small values of the view factor for a vertical respective a horizontal target at floor level compared to the accepted view factor for a 25 meter high flame

Figure 26: View factor for a vertical respective a horizontal target at a level of z=12.5 meter compared to the accepted view factor for a 25 meter high flame

Figure 27: Expanded scale for the low values of the view factor for a vertical respective a horizontal target at a level of z=12.5 meter compared to the accepted view factor for a 25 meter high flame
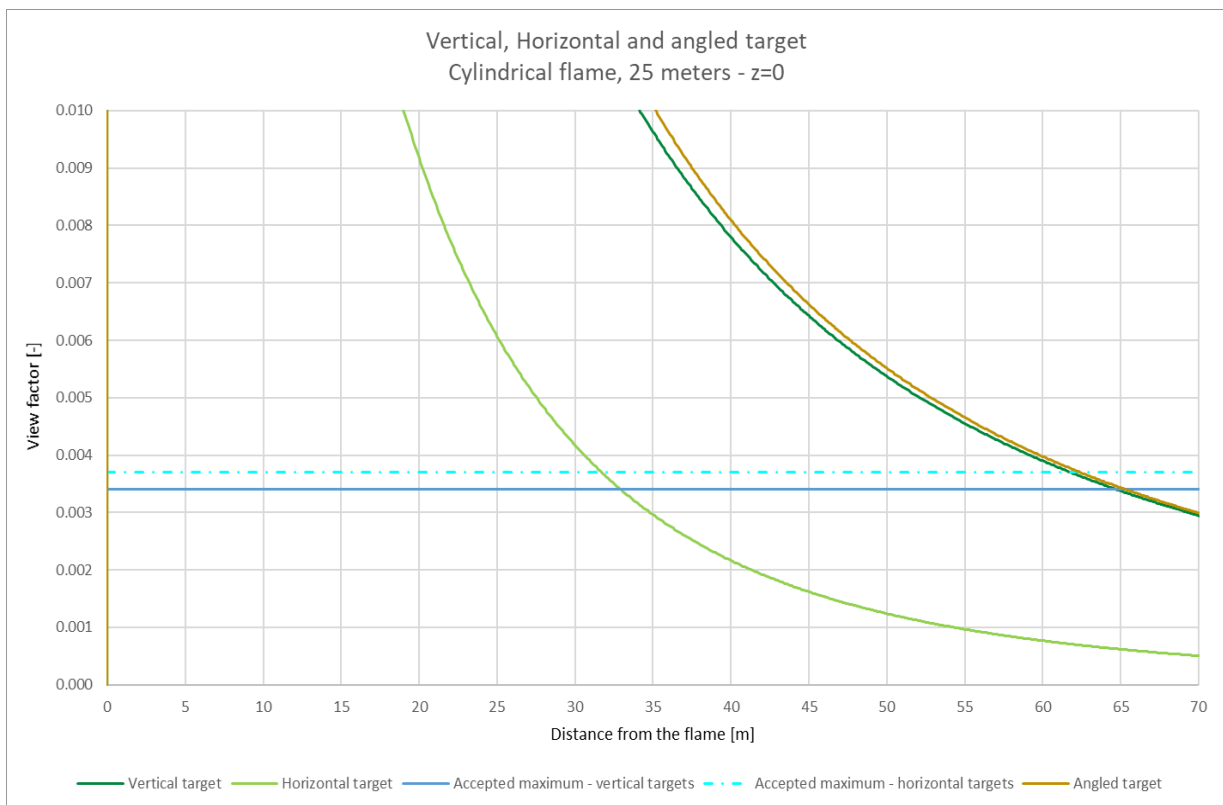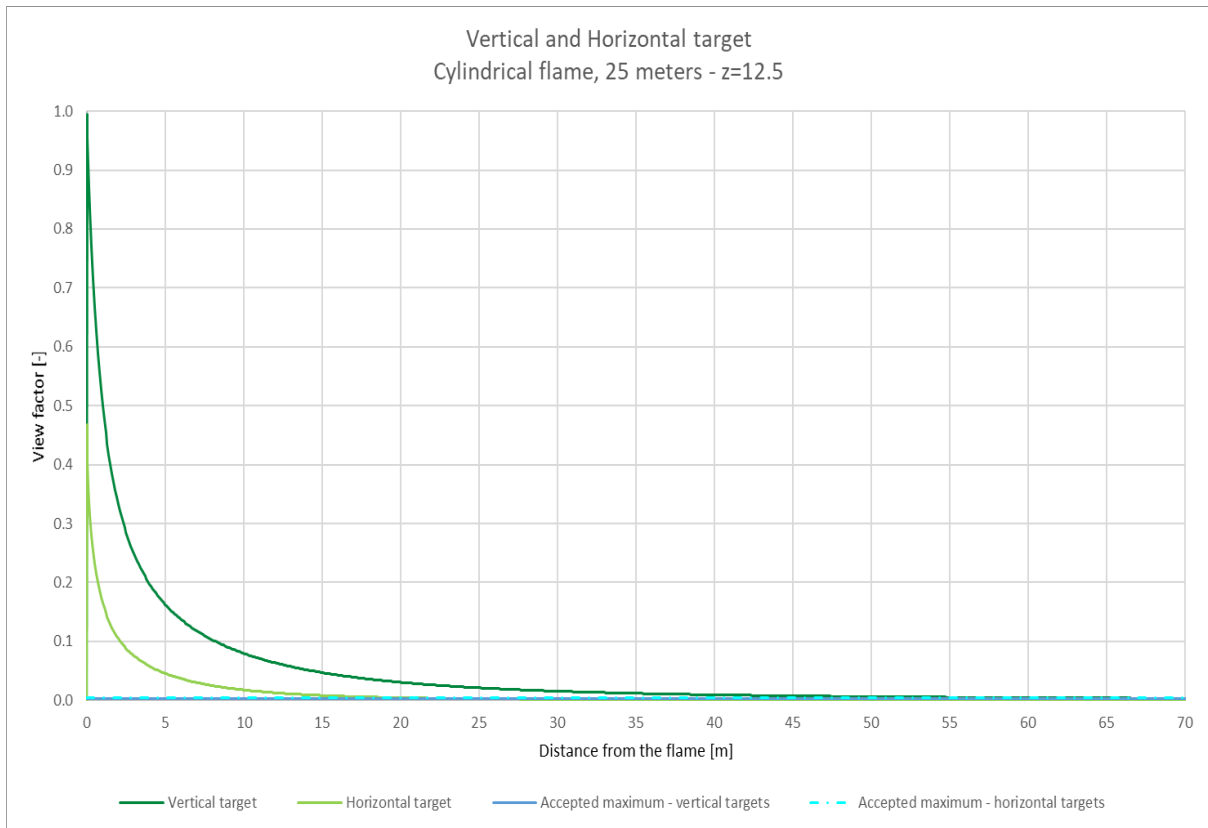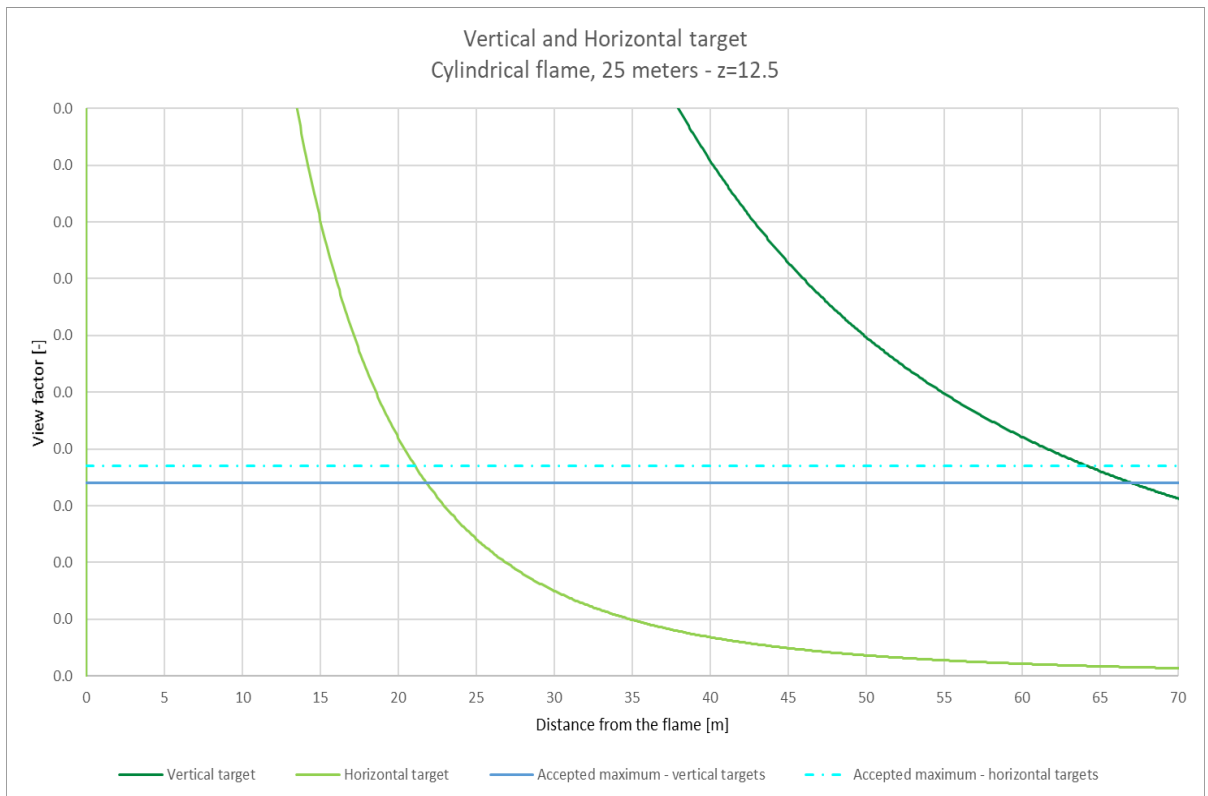
31

The distance where the maximum allowed view factor is reached, and thus the maximal accepted adiabatic surface temperature, as a function of the height of the flame is presented below, see Figure 28 to Figure 31. The first two graphs show the distance for a vertical respective a horizontal target for a 15 meter high flame and the second two for a 25 meter flame.

Figure 28: The variation in distance at which the acceptable radiation temperature is reached due to the height for a 15 meter high flame and a vertical target

Figure 29: The variation in the distance at which the acceptable radiation temperature is reached due to the height for a 15 meter high flame and a horizontal target
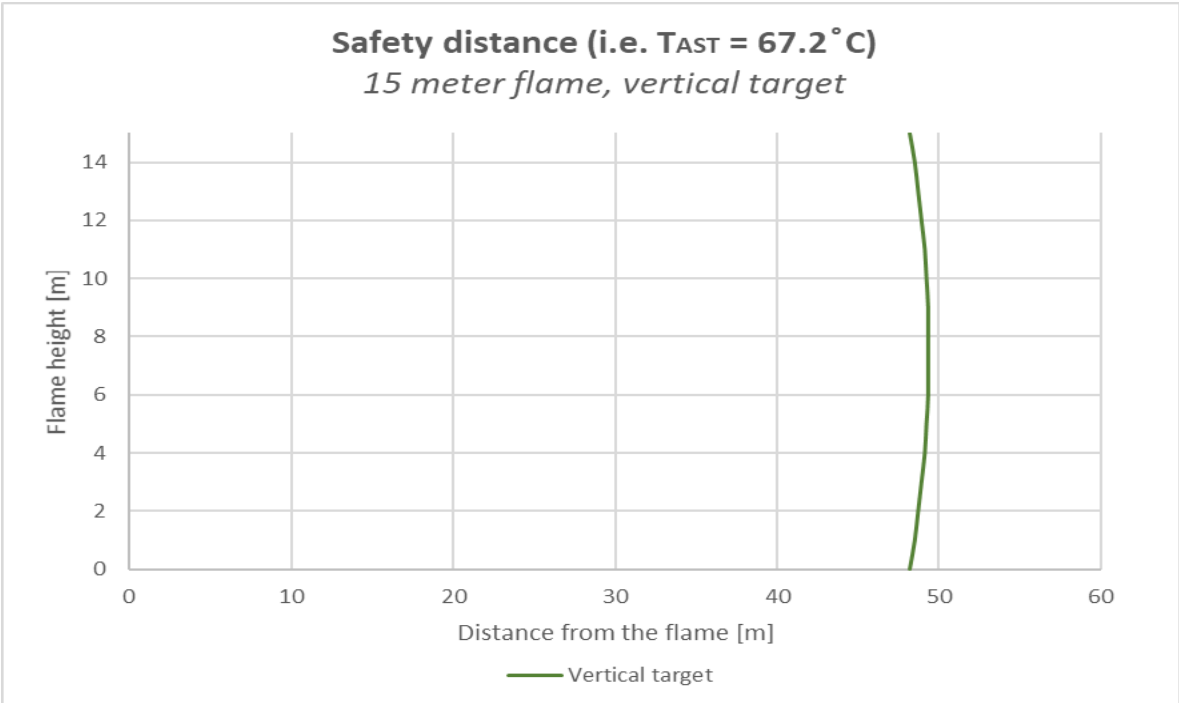
Figure 30: The variation in distance at which the acceptable adiabatic temperature is reached due to the height for a 25 meter high flame and a vertical target
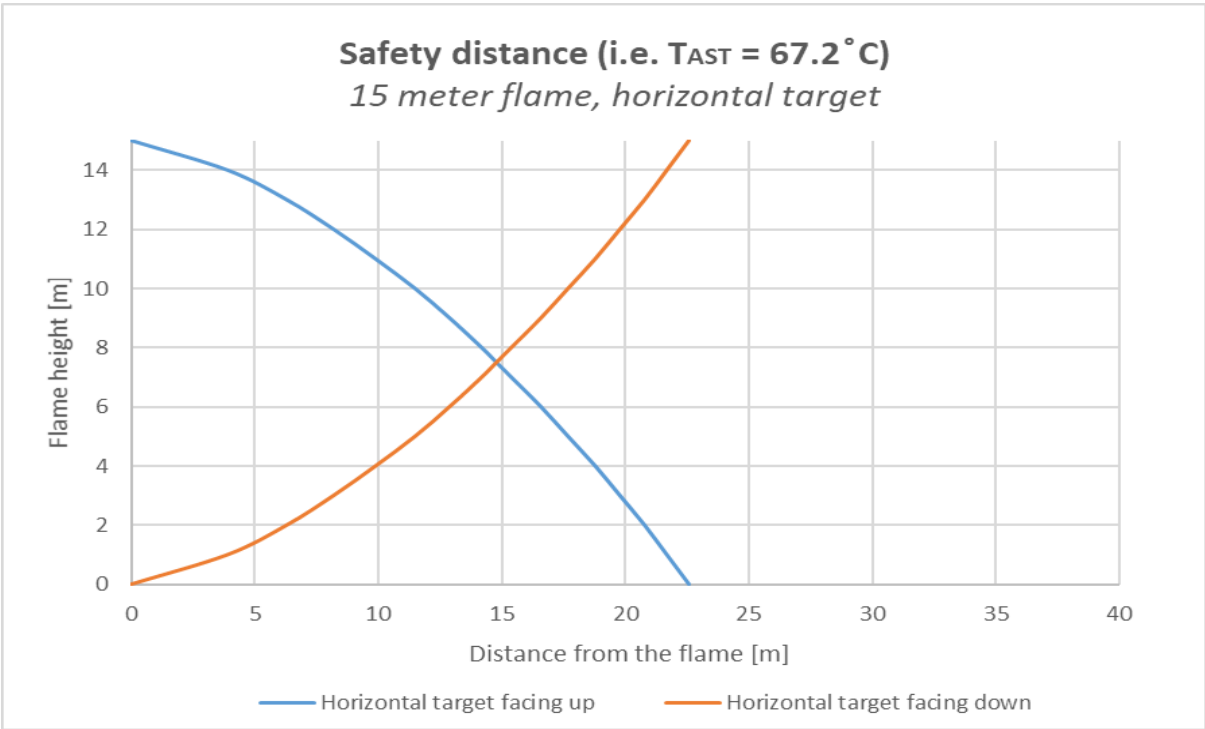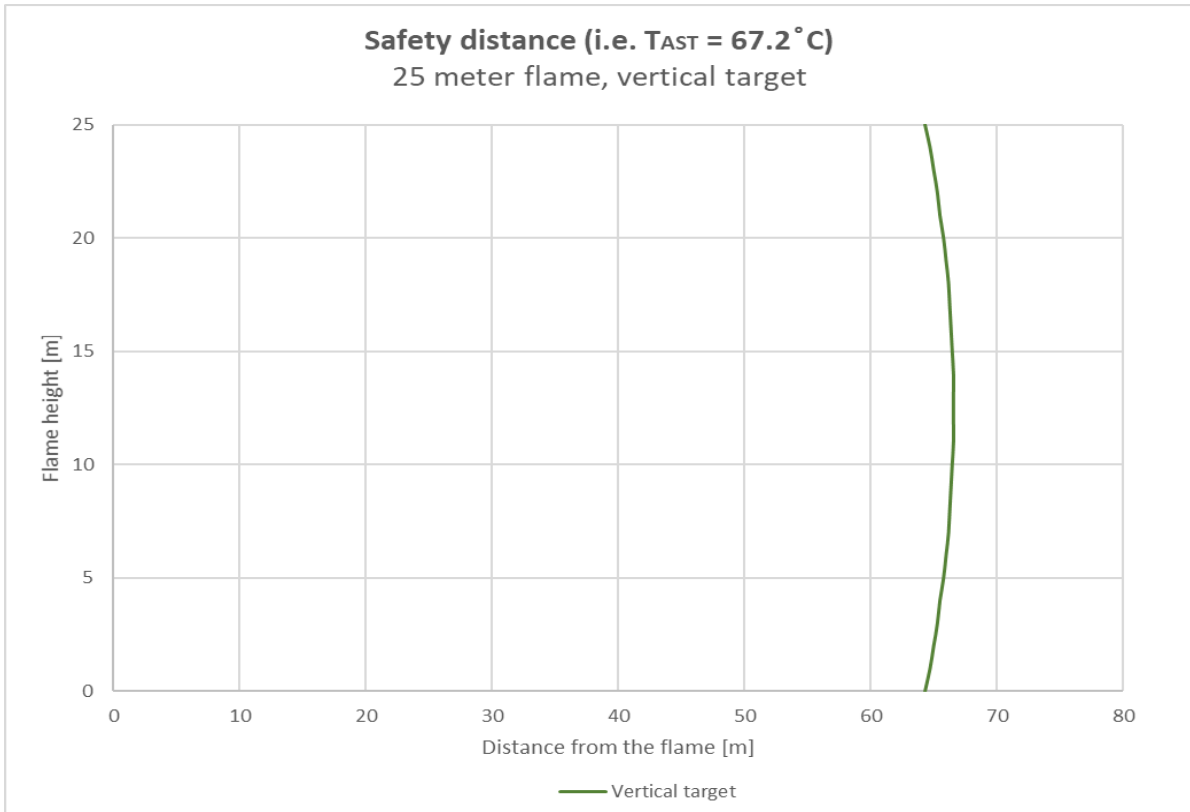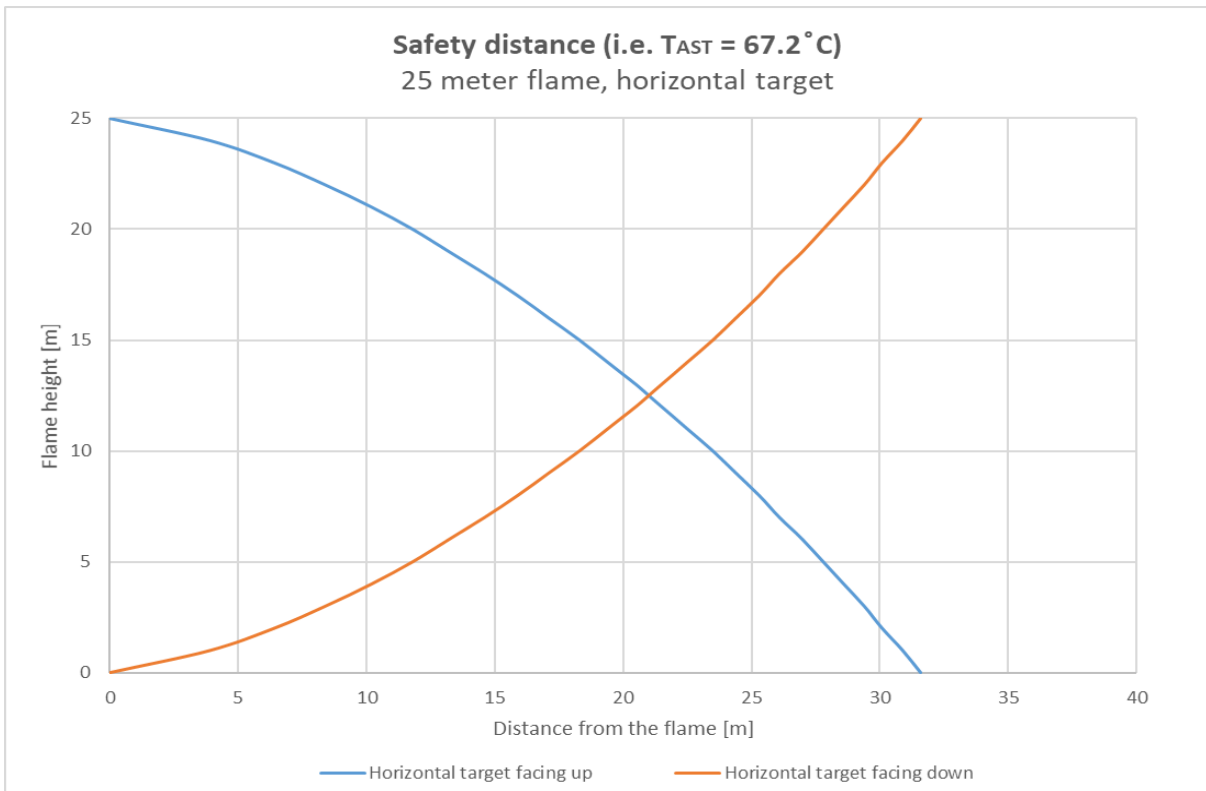

Figure 31: The variation in distance at which the acceptable adiabatic surface temperature is reached due to the height for a 25 meter high flame and a horizontal target

The results above show that the acceptable adiabatic surface temperature is reached further from the flame for a vertical target and at a significantly closer distance for a horizontal target independent the flame size. Thus, the incident radiation reaching a horizontal target is also distinctly lower. Further, a distinct difference when studying a vertical respective a horizontal target is shown. For a vertical target the adiabatic surface temperature reduces more at the bottom and the top than in the middle of the flame. This due to that the influence of the radiation from the flame to a vertical target is more intense at the middle of the flame. The opposite trend is found for a horizontal target. This since the surface for which the adiabatic surface temperature is calculated only is affected from one part of the flame when the target is above floor level. The radiation from the other part of the flame reaches the opposite side of the horizontal target, which blocks the radiation from reaching the relevant surface. A horizontal target can accordingly be considered shadowing itself. The safety distance for a flame is determined by the largest distance from the flame where the acceptable adiabatic surface temperature is found. For a flame of 15 meters this distance equals 49 meter, and 67 meter for a 25 meter high flame.

Discussion and Conclusions

The objective of this study is to find a generic expression to compute a safety distance to a target from a sonic jet flame based on earlier reported experiments. However, no studies have been found that fulfil these generic conditions. Only equations based on results from experiments for specific jet flames have been found. Computations using these equations have been compared and evaluated to assess if it is possible to apply any equation for a general jet flame independent of the fuel. Consequently, as these equations are based on specific conditions a number of assumptions are needed both regarding the equations as well as some of the parameters within these. These assumptions lead to uncertainties and in order to achieve results that are on the safe side the assumptions have been made accordingly.

The result of this study therefore gives a relative large safety distance if the requirements from NFPA 160 shall be fulfilled. The safety distance is according to this study approximately 49 meters for a jet flame with the flame height of 15 meters and 67 meters for a jet flame with a flame height of 25 meters. According to the performed literary survey no generic arithmetic methods have been found to calculate mass flow, energy release rate or the flame temperature for jet flames independent on fuel. When reviewing the results for the energy release rate they are found to vary significantly, between 83MW and 123MW for a 15 meter flame and 93MW and 313MW for a 25 meter flame. The variation shows the uncertainties when computing the energy release rate using the equations 2, 4 and 5 of this study that were found in the literary survey. The difference in computed energy release rates might depend on the variation of exit velocity and fuel. This applies both for the reported experiment used to determine the mass flow of fuel, which is then used in equation 2 and 4, and the reported experiment for which the relation between the flame height and the energy release (equation 5) is based on. However, the documented relation between the flame height and the mass flow of fuel is here assumed to be true for all types of fuels. This since the mass flow is given in kg/s and independent on which fuel used, the same amount of fuel in kg/s should generate the same flame height if the outlet velocity is the same. Hence the error is in this case first and foremost assumed to depend on the variation in exit velocity. Unfortunately, the relation between the mass flow and the flame height is based on experiments including smaller flames than the flames focused on in this project. Extrapolation over a wide flame height range thus had to be made, which also contribute a source of error. The relationship between the flame height and the mass flow rate showed a linear trend, that was used when doing the extrapolation. This results in systematic errors as a result when adapting the line to the experimental values. Due to the lack of experimental data this source of error is palpable. To get more accurate values more experiments have to be conducted including larger jet flames. Since all curves, independent orifice size, in Figure 2 shows a linear trend a linear relationship between the flame height and the mass flow rate is assumed to be reliable. The possible error of the calculated mass flow rate is thus assumed to be smaller compared to e.g. the flame temperature which is an assumption made based on measurements from different publications and not a function. When utilizing equations 2 and 4 specific fuel parameters are used, which indicates that these approaches can be adapted independent of fuel. This is not the case in equation 6 where no specific fuel dependent parameters are used. However, no enlightenment has been found why the different equations generate variable values of energy release rate in any earlier publications.

The flame temperature computed by equation 8 equals 872 $^{\circ}$C independent on the energy release rate in the flame region, which shows an uncertain when equation 9 is applied to jet flames. Furthermore, 872 $^{\circ}$C is considered too low for large flames of 15 to 25 m. The likely reason for the low temperature is that equation 8 is normally used for pool fires. Hence, the result of the calculated

flame temperature in this study shows that the assumption that equation 8 possible also could be applied to jet flames is not correct. Thus, an assumed flame temperature of 1200 $^{\circ}$C was used in the calculations of this study, which potentially result in a too large safety distance. Based on previously documented values through measurements during conducted experiments is it assumed to be very unlikely that the flame temperature for a jet flame of this type should exceed 1200 $^{\circ}$C. However, to be absolutely sure, an experiment with the flames of focus in this study would be needed.

Multiple methods were found during the literature survey for calculating the emitted heat flux of jet flames. None of these equations generated the same results which indicate an uncertainty in the input parameters used to calculate the maximum accepted view factor. The variation in the calculated $\dot{q}_{emi}$ might depend on the specific fuel used in the earlier studies when equations 20-27 were derived, as well as in the characteristics of the jet flames such as sonic versus subsonic regimes. Therefore, it would be of great value to perform experiments with various fuels and velocities as well as geometrics of the flames to determine a generic expression for jet flames independent the fuel.

Additionally, if the needed parameters, e.g. the heat of combustion and emissivity, would be known for Isopar L the result would likely be more robust. However, this is not expected to result in a larger safety distance since a worst case scenario has been considered for the calculations in this study. One question that might be relevant is thus if it can be accepted to use a fuel that lacks information on vital parameters needed to perform fire safety engineering calculations.

Having knowledge of the relevant properties of various fuels would make it possible to develop a generic expression for the mass flow, energy release rate and the emitted heat flux. Most important though would be to develop a generic expression to calculate the flame temperature for jet flames (both in subsonic and sonic regimes) based on flame height and orifice outlet similar to expressions that exist for pool fires today. No expression to determine the flame temperature adapted for jet flames was found in the present literary survey, thus an assumed flame temperature had to be used. If the flame temperature could be calculated and the specific parameters for the fuel used would be known, both the accurate incident radiation and the emitted heat flux could be computed. This could help facilitate the ability to increase the fire safety regarding both pyrotechnical events and in various industries such as off shore, refineries and petrol stations. This includes for instance the designing and dimensioning of different facilities with more precise dimensioning in structural elements and frameworks. Thus, increasing knowledge within the area of jet flames might not just result in increasing safety, but also in optimizing industrial structures with its impact on economic expenses.

Furthermore, the view factor for a horizontal target decreases faster with distance when located in the middle of the flame, which was expected based on the calculations and assumption utilized. This depends on that only part of the flame is considered i.e., when z $\neq$0 the target is turned away from a part of the flame. Thus the incident radiation from the flame to the target is reduced. However, it can be discussed if the reduction of the incident radiation always should be considered. Depending on which temperature that is of interest (e.g. the temperature within the material) one might have to consider the influence from both parts of the flame. This since the object might receive radiation on both sides which through conduction will affect the temperature within the target. In this case the variation in the view factor due to the height will differ and it will instead be larger in the middle of the flame.

Since the jet flames examined in this project is placed outdoors, the effect of the wind can result in a tilted flame to various extents. This can lead to that the view factor differs from day to day, which has not been considered in the above investigation. The jet flames of focus in this project is

permanently installed outdoors and is expected to be fired every day for at least 5 years the wind effect must be accounted for when determining the safety distance. However, the safety distance calculated in this project is based on multiple assumptions where each time the worst case has been considered to be sure that the resulted safety margin is enough. It can thus be assumed that the effect of wind not will generate a larger safety distance than what has been calculated in this study. Finally, when comparing the view factor for a vertical target and a horizontal target the result was as expected, i.e. the view factor for a vertical target is larger, and most distinctly at a closer distance to the flame. However, at floor level, where also the view factor for an angled target could be calculated, an even larger view factor was computed and thus the largest safety distance. The difference of the view factors for an angled and a vertical target at large distances from the flame is very small. Thus, the safety distance was found to be the same for an angled target and a vertical. However, the safety distance for a vertical target placed at half the flame height was found to be larger than for an angled target at floor level. The acceptable distance found for vertical targets have thereby been used to determine the safety distance.

Concluding, this study has shown that there is still a lot of knowledge left to gather concerning jet flames. Further research within the area is recommended, and first and foremost including large scale experiments with various fuels including flames in both subsonic and sonic regimes. Many necessary assumptions have been made during this project, which leads to a large margin of error in the end result. The assumptions which are considered to have the most influence on the result are the flame temperature and the flame emissivity. However, the assumptions have been made to make sure that the result would be on the safe side. This resulted in that the maximum accepted temperature where calculated to be obtained at a distance of 48 meters respective 64 meters for the different flame geometrics. In order to avoid these uncertainties there is, as mentioned above, a need to perform more studies related to jet flames of larger scales.

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The developed flame effect plan is presented in this appendix. The flame effect plan has been developed together with experts within the pyrotechnical field and the management group for this specific project . Below are parts of the flame effect plan presented. Some parts, such as e.g. specific technical features and manufactures, are privacy classified which thereby have been covered. The flame effect plan is presented in its original formulation and thus the font will differ from other parts of this report.

Flame Effect Plan

[To be completed by operators who intend to use flame effect system at Dubai Festival City]

Event Information

Event Organisation:

Laservision Mega Media LLC

Contact information:

Laservision Mega Media LLC
Dubai Festival City
Festival Tower 19th Floor, Office 1935
Festival City, Dubai, UAE

Event Name:

Dubai Festival City

Event Schedule:

Each day, for a time span of five to ten years, approximately six shows a day will take place. The time may come to vary, but the table below shows a rough estimation of when the shows will be initiated.

	First show	*Second show*	*Third show*	*Fourth show*	*Fifth show*	*Sixth show*
Time	14.00	16.00	20.00	21.15	22.30	23.45

Event Location:

Dubai Festival City, Old Marina, Dubai.

Overview

The following document describes the requirements for flame effect operation included in the multimedia show at Dubai Festival City. The flame effect operation must obtain prior authorization and pre-approval by the authority having jurisdiction. If changes are to be made to the show regarding the utilization of the flame effects in a way that is not covered in this document, a revised flame effect plan must be submitted and approved before operation.

All flame effect operators and their assistants are responsible for their own equipment and its use. Because of the dangerous nature of flame effect, no one may display, exhibit or discharge any flames

that are automated, switched, or pressurized without authorization. Responsibility includes verification by testing that an installation or performance will not endanger participants, operators, audience or members of the fire safety team.

Laservision Mega Media LLC holds the overall responsibility of the production of the shows. Shared responsibility concerning manufacturing of the flame effect falls on SFX Controllers Sweden AB. Detailed description of the effects and the manufacturing are included in this document. The flame effect operation will be conducted by Laservision Mega Media LLC, which provides both operators and assistants.

Document Revisions

Contact information

Name of Person Responsible for flame effect on location (operator):

_____

Phone Number:

_____

Email Address:

_____

Postal address:

_____

_____

_____

Social security number:

_____

Name of additional flame effect operators:

_____

_____

_____

Name of additional fire safety assistants:

_____

_____

_____

_____

All operators and assistants must be 21 years of age or older and have the proper training and knowledge about the system.

Flame effect operation dates and times:

Specific date and time shall be presented below.

_____

_____

_____

_____

_____

Flame Effects

Flame effects classification:

The flame effect that is used is classified as V by using the table taken from NFPA 160 guidelines as a guide. See table below.

Flame effect group	Control Type	Minimum Control Requirements
I	Manual controls	1. No automatic controls shall be required.
II	Automatic controls	1. Ignition supervision shall be provided. 2. Automatic shutoff shall follow failure
III	Automatic controls	1. Manual operation of the effect valve shall be permitted. 2. If the operator cannot confirm the pilot or direct ignition source for the flame special effect, a primary safety control shall be installed. 3. Two fuel shutoff valves, one of which will be a safety shutoff valve, shall be provided and installed in series.
IV	Automatic controls	1. Primary limit device(s) shall be installed as required. 2. A fuel supervisory station shall be installed with fuel pressure limit switches to control the supervisory station valves. 3. Each flame effect burner shall be equipped with a primary safety control and an effect valve. 4. A flame effect safety control system that is capable of safely operating the entire flame effect consistently for repeated cycles shall be used.
V	Automatic controls	1. The requirements for Group IV shall apply. 2. A flame effect safety control system that is capable of safely operating the entire flame effect consistently that is sequenced by the main control system shall be used. The flame effect safety control system shall maintain all of its internal safety features, with the interface between the flame effect control system and the main show control system limited to those commands and status indicators that cannot alter or override the flame supervisory system control logic.

4

VI	Automatic controls	1.	The requirements for Group V shall apply.
		2.	Where cast members are in close proximity to the flame effect, the flame effect shall be under the active control of a main show control system and a fail-safe positive manual enable (PME).
VII	Manual or automatic controls	1.	Controls shall be as recommended by the designer and acceptable to the authority having jurisdiction.

Number of Effect:

Maximum twelve (12) flame heads are used as a part of the multimedia show.

Flame heights:

The normal operation height of the majority of the flames will be 15 metres. Some flames will reach 25 metres during performance, which is the maximum height of the flame effect.

Fuel Used and the Consumption:

Isopar L is used as fuel. Max 80 litres of fuel per show will be utilized, for a maximum daily consumption of 480 litres.

Additional flame effect specifications:

Location and Production Schedule:

The components are manufactured by different suppliers. The manufacturing is done in Sweden, predominantly in Västra Götalands Län. For other cases, the location is specified below.

Product	Manufacturer/Supplier	Location	Date
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████	████	████	███
██████			
██	███████████	██	██████
████	████	██	██████
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██	█████	██	████
██████	████	████	██████
█████	████	████	██████
███████	████	████	██████
█████	████	████	██████
███	██	████	████
█████	██	██████	██████
███	██	████	████
██████	█████	████	██████
█████	████	█████	██████
███	██	████	████
█████	█████	████	██████

Flammable materials piping:

The piping containing flammable materials, in this case Isopar L or D60, which is the fuel used, is shown in appendix 1, figure 3.

Storage and holding areas:

The fuel drums will be stored in a controlled-access unpressurized space, air-conditioned 30º-35º C, surrounded by a bunt wall.

Maintenance:

Each month, all-around maintenance of the entire flame system will be made. The maintenance will be executed by a certified technician that is familiar with the system. Furthermore, testing of the flame effect system shall be completed before each performance to guarantee that it works accordingly. Pre-operation tests shall be made by the operator or assistant operator in charge on set.

Additional fire protection features:

According to local regulations, the building in question is classified as temporary. Consequently, no additional fire protection features are required.

Additional fire extinguishers and/or fire safety devices:

Fire extinguisher will be placed within the Centrepiece. No additional fire safety devices will be installed in the building.

Emergency response procedures:

Because construction is currently in progress, emergency response procedures have not yet been put in place. Before the flame effect plan is approved, describe the current emergency response procedure below.

_____

_____

_____

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_____

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_____

Means of egress:

Detailed information regarding the means of egress will be available when construction of the site is completed.

Material Safety Data Sheet (MSDS):

MSDS for Isopar L fluid is presented in appendix 4. Because the supplier of the fuel is not yet determined, the material safety data sheet attached in this document is from a previous supplier. However, the material safety data sheet is up to date.

Product information and material safety data sheets for the relevant components included in the entire system (pump system, control system, etc.) are presented in appendix 4.

Documentation of Flame Retardant Material:

Because no flammable material is used in the construction of the flame effect system, no additional fire retardant materials have been used. For more information about a specific material or component used, see specific material safety data sheet in appendix 4.

Additional Documentations

Operation Instructions:

Operation instructions for flame effect system are available for the authority having jurisdiction after contact with the operator.

Safety Requirements

Operators and assistants:

Operators and assistants shall possess good knowledge of the system and performance and must be 21 years of age or older. A knowledgeable representative of the installation or performance shall serve as a contact person to the Fire Safety Team. His or her role is to provide the Fire Safety Team with information about the installation and performance. This may include changes to description of the installation or performance schedule, safety- or emergency plan and so forth.

Approval:

The operator must complete and submit a Flame Effect Plan prior to the event and have it approved by the *Authority having jurisdiction*. Furthermore, he or she must ensure that the system and flame effect works according to design, including fuel distribution and safety features such as valves, switches and emergency stop, prior to any event. If any error within the system is noticed during the inspection of the system and flame effect prior to an event, it must be corrected before performance commences.

Safety Requirements:
- Flame effect may only be operated by those identified in the plan as operators or assistants under the supervision of operators
- All operators and assistants must be trained in the use of fire extinguishers
- Operators and assistants are prohibited from being intoxicated or under the influence of alcohol or drugs during the operation of Flame Effect
- Only people familiar with the safety considerations and hazards involved are permitted to complete fuel loading operations. Wearing appropriate personal safety gear is required
- No negligence, carelessness or unsafe conditions with Flame Effect are tolerated
- Open flames or smoking are prohibited within the event area, with exception from the flame effect used in the performance
- Entering the affected area during operation of the system is strictly prohibited

Daily Safety Check

- A daily check of the system, including all safety features, is mandatory before performance begins
- All areas of the site where flame effect materials and devices are ignited must be inspected before start-up and after shutdown of the system
- The locations where flame effect devices are installed or fired shall be inspected to ensure that neat and orderly conditions are maintained

Fire Extinguisher

- A Dry Chemical Fire Extinguisher must be available in case of accidental fire with any flame effect installation.

Notes about Fire Extinguishers

Additional fire extinguishers, if needed due to specific fuel, specific materials located within the area, electricity etc., shall be available on site. Controls, service and refilling of the fire extinguishers shall be made according to recommendations for each type of extinguisher. Dry chemical extinguisher start to lose charge after a single discharge and must therefore be serviced and refilled after each use.

First Aid

- A basic first aid kit consisting of material suitable in case of burn injuries should be available on site. Operators and assistants should have basic knowledge in how to treat mild burns. In case of severe burns, they shall be treated by Emergency Medical Services.. In case of fire on a person's body or clothing, stop where you are, do not run, drop to the ground and roll to put out the flames. Cool the burn right away with water and seek medical help.

Cleaning of the premises

- The operator and assistants are responsible for all clean up at the installation site after the performance
- The premises must be kept in a neat and orderly condition
- Accidental spillage of material must be properly taken care of by the operator or assistants using "Spill Clean-up Material" such as shovel, rake, metal garbage can, etc.

Fuel Safety

- All liquid fuel containers must be clearly labelled. Original labels are preferred
- A dry chemical fire extinguisher must be kept visible near the storage location of any liquid fuel
- A supply of fuel absorbent material (i.e cat litter) must be kept near any spills collection area.
- All fuel tanks and holders must be secured and monitored or placed where they are not accessible to unauthorized people
- The maximum permitted volume may not be exceeded. Additional fuel must be placed in secondary containment area

Note: For detailed fuel safety instructions and extinguish measures for a specific fuel, see material safety data sheet. Adjusting the approach can reduce the spread of the fire, increase the efficiency of the extinguishing of the fire as well as increasing the overall safety for both people and equipment.

Notes about Fuel Safety

- Keep all equipment in good condition. Watch for leaks, deterioration, or damage
- If fuel is spilled on a person's body or clothing, move away from any ignition source. First aid measures and instructions could be found on the material safety data sheet for the specific fuel used
- Be aware of static electricity and machineries as well as equipment that may produce sparks. Sparks may ignite the flammable mixture formed by vaporised fuel together with the oxygen in the surrounding. The concentration necessary to create a flammable mixture of vaporised fuel and oxygen depends on which fuel used. See material safety data sheet for the specific fuel used for more information.
- A pump shall be used when transferring fuel. Do not siphon using your mouth; ingestion of fuel can be fatal. For certain fuels, it is vital to not induce vomiting if ingested. For more specific details for the fuel utilized, see material safety data sheet.

Definitions

- **Operator** – An individual authorized to operate the flame effect
- **Assistant** – An individual authorized to assist in the safe operation of the flame effect and ensure the safety of the audience and potential people authorized to be located on certain areas on the site.
- **Installation** – All equipment related to the flame effect
- **Performance** – The usage of the flame effect