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Flame height: Effect of one- and two-sided boundary surfaces

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Master Thesis in Fire Safety Engineering

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Flame Height: Effect of one- and two-sided boundary surfaces

Master thesis in Fire Safety Engineering

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This thesis is a part of the master's program in Fire Safety engineering at Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented, the conclusion and the assessments done in the thesis.

Preface

This study is a master thesis that is the culmination of a two-year full-time study in Fire Safety Engineering at Western Norway University of Applied Sciences. This study spans two semesters, beginning in early autumn 2020 and ending in late spring 2021.

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I will give my supervisors a huge thank you for the help during the writing of this thesis, their guidance has been much appreciated. I would also thank my family and friends for the support during this process. A special thanks to three of my fellow students, Magne, Ernst and Ankush.

Abstract

Theory suggests that fires placed flush to one- and two-sided boundary surfaces will have an increase in flame height independent of fuel used and size of the fire. Meaning the flame height will increase when flush to a wall and corner for gaseous and liquid fires in small- and large-scale fires. It is published equations to calculate the mean flame height which are based on previous fire experiments [1].
This thesis investigates the behavior of fire conducted in small- and medium scale experiments with three different configurations: open fire, one- and two-sided boundaries. Fires with energy release rate ranging from 6.33 kW to 114 kW using different width square pans. The experiments were carried out to investigate the effect of the three configurations with different sized fires, with regard on the flame height and to see if these configurations had a different outcome when using two different fuels, propane gas and liquid heptane. There were conducted 45 medium scale experiments and 18 small-scale experiments to provide a range of data to compare. It is used dimensionless analysis to determine the relationship for flame height and intermittency for buoyant diffusion flames for the three configurations. For a sequence of photos, the flame height was determined by visualization.

The experimental results show that the flame height does change when exposed to different boundaries, but not to the extent that was expected. It is shown that the increase in flame height is different for gaseous and liquid fires, as well the size of the fire. Based on the presented data in this thesis a simple model for predicting the effect of one- and two-sided boundaries on the mean flame height are presented by using Heskestad's approach to estimate the dimensionless mean flame height [2].

The increase in flame height is between 10 to 40 % for propane fires when placed next to a one-sided boundary, and 80 to 100 % when placed next to a two-sided boundary. For the heptane fires the increase was higher than the propane fires, giving between 70 to 100 % increase in flame height when placed next to a one-sided boundary, and between 200 and 400 % when placed next to a two-sided boundary.

Sammendrag

Teorien antyder at en flamme som er plassert inntil en- og tosidig grenseoverflate vil ha en økning i flammehøyde uavhengig av brensel og størrelse på brannen. Flammehøyden vil øke inntil en vegg og et hjørne for både gass og væske branner i liten og stor skala. Det er utviklet likninger for å kalkulere flammehøyden som er basert på tidligere eksperimenter som er blitt utført [1].

I denne oppgaven blir en branns oppførsel undersøkt i liten og medium skala med tre forskjellige konfigurasjoner: åpen flamme, en – og tosidig grenseoverflate. Det ble benyttet kvadratiske kar hvor energiproduksjonen varierer fra 6.33 kW til 114 kW for brannene benyttet. Eksperimentene ble utført for å undersøke effekten de tre konfigurasjonene med ulik skalering vil ha på brannen med tanke på flammehøyden, og for å se om de forskjellige konfigurasjonene ville gi et annet resultat ved bruk av to forskjellige brensler som propangass og flytende heptan. Det ble utført 18 eksperimenter i liten skala og 45 eksperimenter i medium skala for å skaffe en variasjonsbredde av data som kan sammenlignes.
For å presentere resultatet er det benyttet dimensjonsløs analyse for å konstatere forholdet til flammehøyden og dens flytende diffusonsflamme for de tre konfigurasjonene. For å fastsette gjennomsnittlig flammehøyde for hvert forsøk ble det tatt en sekvens med bilder hvor hvert bilde ble analysert visuelt og kalkulert.

Resultatet fra eksperimentene viste at flammehøyden vil øke når flammen er eksponert for vegg og hjørne, men ikke i den grad som var forventet. Resultatet viste at økning i flammehøyde var forskjellig fra gass til væske, samt størrelsen på brannen. Basert på den presenterte dataen i denne oppgaven er det foreslått en likning som kan brukes for å estimere effekten fra en- og tosidig grenseoverflater har på flammehøyden ved å bruke Heskestads tilnærming for å estimere den dimensjonsløse gjennomsnittshøyden.

For eksperimentene som ble utført med propan hadde brannen en økning i flammehøyde mellom 10 til 40 % når den var plassert inntil en vegg, og mellom 80 til 100 % når den var plassert inn i et hjørne. For eksperimentene som ble utført med heptan hadde brannen en økning i flammehøyde mellom 70 til 100 % når den var plassert inntil en vegg, og mellom 200 til 400 % når den var plassert inn i et hjørne.

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Definitions

A_f	Horizontal burning area of fuel	[m^2]
c_p	Specific heat at constant pressure	[kJ/ (kg K)]
C	Boundary factor	[-]
D	Diameter	[m]
Fr	Froude number	[-]
g	Acceleration due to gravity	[m/s^2]
$k\beta$	Material constant for liquid fuels	[m^{-1}]
L	Length	[m]
$\frac{L}{D}$	Dimensionless flame height	[-]
$\dot{m}$	Mass flow rate or mass burning rate	[kg/s]
$\dot{m}''$	Mass flow rate or mass burning rate per unit area	[kg/s m^2]
$\dot{m}''_\infty$	Asymptotic mass loss rate	[kg/s m^2]
$\dot{Q}$	Energy release rate	[kW]
$\dot{Q}_c$	Convective part of energy release rate	[kW]
$\dot{Q}^*$	Dimensionless energy release rate	[-]
T_∞	Ambient air temperature	[℃ or K]
u	Velocity	[m/s]
ΔH_c	Complete heat of combustion	[kJ/kg]
ΔH_{eff}	Effective heat of combustion	[kJ/kg]
ρ_∞	Ambient air density	[kg/m^3]
χ	Combustion efficiency	[-]

1 Introduction

1.1 Background

One of the most important factors leading to rapid growth of a building fire during its early stages is the heating of combustible objects in a compartment by diffusion flames and buoyant plumes formed above a fire source. The height of the flame and the temperature of the characteristic plume are practical ways to assess this aspect of fire safety. Because of the reduced entrainment, it is usually assumed that if the fire source is positioned against a wall or corner, flame height and plume temperature will be significantly higher than in the unconfined scenario [3]. There have been presented some practical models of enclosed fires to estimate deterministic properties such as mass flow rate and temperature of fires placed flushed to a wall or a corner. These methods are based on the assumption that an imaginary fire source exists on the opposite side of the wall, with the same intensity as the real fire source. The imaginary fire source assumes that a fire placed flush to a wall will be twice the size of the actual fire source and for a fire placed flush to a corner will be four times larger than the actual fire source [3].

In previous research there have been conducted experiments for vertical boundary surfaces. By using Heskestad's correlation, the centerline temperature rise ($\Delta T_{0(z)}$) of an open fire plume at a height z above the base of a fire can be estimated using Eq. 1 [4]:

$$\Delta T_{0(z)} = 9.1\left(\frac{T_{\infty}}{g c_p^2 \rho_{\infty}^2}\right)^{1/3} \cdot \dot{Q}_c^{2/3} \cdot (z - z_0)^{-5/3} \qquad \textit{Eq. 1}$$

Where T_{∞} is the ambient temperature, g is the gravity acceleration, c_p is the specific heat of air, ρ_{∞} is the ambient air density, $\dot{Q}_c$ is the convective heat release rate, and z_0 is the virtual origin, which is given by

$$\frac{z_0}{D} = -1.02 + 1.4\dot{Q}^{*2/5} \qquad \textit{Eq. 2}$$

Where

$$\dot{Q}^{*} = \frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} \sqrt{gD} D^2} \qquad \textit{Eq. 3}$$

Here *D* is the diameter of the fire base.

When investigating flame height, the non dimensionless flame height (L/D) as a function of dimensionless energy release rate($\dot{Q}^*$) is often used.

Heskestad cites studies that examined the effects of walls and corners on the fire plume. To account for the effect of a wall or corner, a simple modification to Eq. 1 is presented which multiply the heat release rate and HRR by a factor of 2 and 4. The idea behind this is that by evaluating their mirror reflections in Eq. 1, the temperature and entrainment rate of fires can be estimated [4]. One of the goals for this thesis is to provide experimental data that supports or refutes this simple change.

1.2 Problem statement

The research question of this thesis is: Will flames next to walls and corners (boundaries) burn with a higher flame than a flame in the open? This thesis will investigate how tall the flame will be due to the different boundaries and fuel type and compare the result with previous research.

2 Theory

The flame is the visible part of the fire and is the result of electromagnetic radiation from hot soot inside the flame. This chapter introduce the fire as a phenomena including flames, fire plume and its properties. Further, this chapter will also present flame height and underlaying theory.

2.1 Fire

Flame is a gas phase phenomenon. Liquid and solid fuels must therefore be converted to gas before included in combustion [5]. This conversion is mainly simple evaporative boiling at the surface for burning liquids. Ignition of a liquid results in flaming combustion, in which the fuel undergoes a change of state from liquid to vapor. This conversion involves no chemical changes of the fuel molecules, it simply evaporates from the exposed surface and the combustible vapors combine with air, which then form a diffusion flame that burns [6]. On a fundamental level the mass of hot gas is surrounded by colder gas above a burning source, this causes the hotter and less dense mass to rise, which is caused by the density difference, called buoyancy. The buoyancy flow of flames is categorized as a fire plume [7, 8].

Pool fires (with diameter over 1 m) are characterized by turbulent diffusion flames on a horizontal pool of fuel that is vaporized. By convection and radiation, the liquid absorbs heat from the flames and may lose or gain heat by conduction from the solid or liquid substrate below the liquid layer [9].

2.2 Mass loss rate

The mass loss rate or burning rate is the rate at which solid or liquid fuel vaporize and burn. Mass loss rate, denoted $\dot{m}$, is expressed as mass flow per unit time normally given in kg/s or g/s and can also be expressed as mass flux or mass burning rate per unit area, denoted $\dot{m}''$, normally given in kg/(m^2 s). Since not all fuel supplied to a fire may burn, a distinction is made between burning rate and mass loss rate. Burning rate is the mass of fuel consumed in the fire per unit area and mass loss rate is the mass of fuel vaporized but not necessarily burned per unit area [10]. The terms, burning rate and mass loss rate are synonymous for burning objects when the air supply is unlimited [11].

The asymptotic mass loss rate, denoted $\dot{m}''_\infty$, was found when conducting extensive pool fire experiments for a large range of liquids [11]. The result for diameters larger than 0.2 m gave an increase in $\dot{m}''$ with increasing diameter up to a certain value equal to $\dot{m}''_\infty$. When looking at a pool fire the mass loss rate from free burning pools depends on diameter and two empirical constants. The two empirical constants are a function of the radiative heat flux from the flame toward the fuel surface and characterize as the specific fuel used. When considering these constants, it’s not necessary to determine the two separately for pool fire calculation, only the product. One of the two is the extinction-absorption coefficient of the flame, denoted k, and the second is the mean beam length corrector, denoted β. So, the mass loss rate from free burning pool fires can be expressed as followed:

$$\dot{m}'' = \dot{m}''_\infty \cdot (1 - e^{-k\beta D}) \qquad \text{Eq. 4}$$

Where $\dot{m}''$ is the free burn mass loss rate per area and $\dot{m}''_\infty$ and $k\beta$ are constants and dependent on the liquid used. The diameter, denoted *D*, is assumed to be circular, but square and similar configurations can be treated as a pool of equivalent circular area [1, 11].

2.3 Energy release rate

Energy release rate is the essential characteristic that describes quantitatively the size of the fire and is described to be the most important variable in fire [12]. Energy release rate, often referred to as heat release rate, $\dot{Q}$, is when an object burns and releases a certain amount of energy per unit time, normally given in kW. Energy release rate in a fire depends mainly on the type, quantity and orientation of the fuel, it also depends on the effect an enclosure may have. The energy release rate will vary with time, and the bigger the fire the higher the energy release rate becomes [11].

Direct measurement is the only practical way to determine an item's burning rate or energy release rate, where such measurements are termed free burn measurements. The meaning behind the term free burn measurements, is that the enclosure effect is minimized (hot gases are evacuated away from the fire and the air supply to the fuel is unrestricted). Two of the most common method to determine the energy release rate is by oxygen consumption calorimetry and by measuring the burning rate or the mass loss rate [11].

When looking at the heat release rate for a single burning material, it has been assumed that the rate of burning and the rate of heat release in the flame are coupled. Because of this assumption it has been common to express the rate of heat release as the product of the burning rate and the net heat of combustion of the fuel, and is expressed as [13]:

$$\dot{Q}_c = \dot{m} \cdot \Delta H_c \qquad \text{Eq. 5}$$

This assumption states that the combustion of the fuel is complete, even though natural fires, which involve diffusion flames rather than premixed flames, is not fully combusted. Before combustion takes place, air and fuel must mix through a diffusion process (laminar or turbulent, depending on the size of the fire). So, because the mixing process is relatively inefficient, the products of combustion will contain certain species that are only partially oxidized, such as carbon monoxide, aldehydes, ketones, and particulate matter in the form of soot or smoke, even though excess air is drawn (or entrained) into the flame. This indicates that not all the available chemical energy has been released [13]. So, when knowing that the mixing process is relatively inefficient in a fire the heat of combustion is separated in two. The heat of combustion is a measure of how much energy is released when a unit mass of material combusts and is typically given in kJ/kg or kJ/g. One of the two is the complete heat of combustion, denoted ΔH_c, and is a measure of the energy released when the combustion is complete, resulting in no residual fuel and also releasing all the chemical energy of the material. The second heat of combustion that needs to be distinguished from the former is the effective heat of combustion, denoted ΔH_{eff}, where some residue is left, and the combustion is not necessarily complete [11].

The term "combustion efficiency" refers to how well the fuel being burned is utilized throughout the combustion process [14]. So, when looking at the heat of combustion, the combustion efficiency, denoted χ, is the ratio between the effective heat of combustion and the complete heat of combustion and can be expressed as followed

$$\chi = \frac{\Delta H_{\mathrm{eff}}}{\Delta H_c} \qquad \textit{Eq. 6}$$

Some fuels burn with a flame that is hardly visible, such as methanol (alcohol) and methane (gaseous fuel), that indicated a low production of soot resulting in a combustion efficiency close to unity [15]. For flames that produce sooty flames the combustion efficiency lays typically around 60 to 70 %, assuming there is plenty of available oxygen for combustion [13]. So, with this knowledge the energy release rate can be calculated from various burning materials and can be expressed as

$$\dot{Q} = A_f \dot{m}'' \chi \Delta H_c \qquad \textit{Eq. 7}$$

Where $\dot{Q}$ is the energy release rate, A_f is the area of the burning surface, $\dot{m}''$ is the free burn mass loss rate, χ is the combustion efficiency and ΔH_c is the heat of combustion of the fuel [11].

2.4 Fire plume

Depending on the scenario, fire plumes may be characterized into various categories. The most commonly used fire plume in fire safety engineering is the buoyant axisymmetric plume. The plume is caused by a diffusion flame that is formed above the burning fuel [7].

Diffusion flames are a phenomenon where fuel and oxygen are initially separated, and then mixes in a reaction zone through turbulent and molecular diffusion. When the concentration of the mixture is favorable to combustion, flaming and burning occurs. As mentioned, the diffusion flame mixes together in a reaction zone through turbulent and molecular diffusion, but when the fuel and the oxidant come together through turbulent mixing, the molecular diffusion is the underlying mechanism. So, in other words, this is the process that occurs when the molecules are transported from a high to low concentration. Another type of flame is the premixed flame, where the fuel and oxidant come together before it is ignited [7, 16].

Turbulent flames are described as larger diffusion flame that are unstable, fluctuating with periodic oscillations and shedding large eddies at the flame tip. Eddies also roll up on the outside of turbulent plumes. The reason for these eddies is the relationship between the hot flame and the cold air. This characterizes turbulence, with the random movements, will give rise to periodic flame height fluctuations, as well for the shape of the flame. The shedding of the flame will depend on the diameter of the flame [7]. It has been stated that if the flow rate in a gaseous fire is low the flame does not fluctuate, but when increasing the rate, the length starts to fluctuate, meaning the critical flow speed decreases as the diameter of the fire increases. Fluctuation in a gaseous flame is also dependent on the nature of the gas. Oscillations depends on the speed. As the speed increases the type of oscillations alters resulting the upper part of the flame to shed and continues to burn in isolation. For liquid fires the oscillation also varies with the diameter, meaning the upper part of the flame tends to break/shed as the diameter increases [17].

McCaffrey [18] found that the fire plume consists of three distinct regimes (see Figure 1): the near field above the burning surface, this is the area where the flame is persistent and where the flame has an accelerating flow of burning gases, which is called the flame zone. The second distinct regime is in the region where there is an intermittent flaming, as turbulence are shedding at the edge of the flame, and where the flow velocity is near constant. The fluctuations in this region are caused by periodic oscillations, which occur at a frequency of 1-3 Hz and are dependent on the diameter of the fire [7], this region is called the intermittent zone. And third distinct regime is the buoyant plume and are characterized by decreasing velocity and temperature as function of height [8].

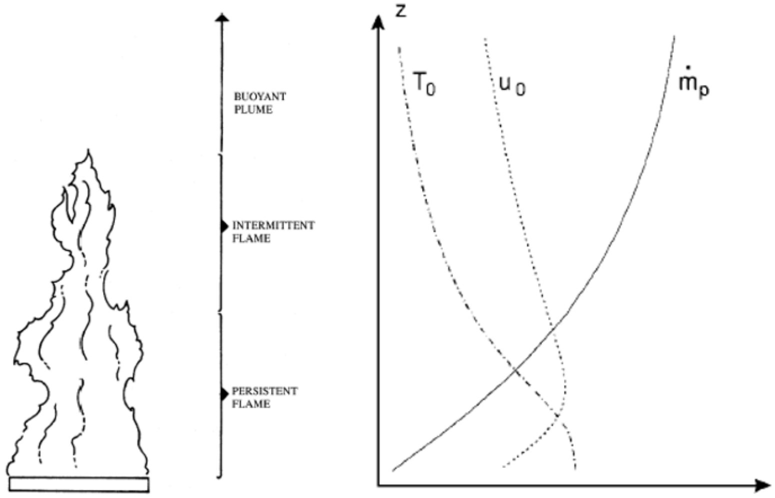

Figure 1 The three zones of the McCaffery axisymmetric buoyant plume, where the right-hand side of the figure shows how plume properties change with height. In terms of the vertical scale, the two figures do not correspond [7, 8].

The mathematical model of the simple buoyant plume is based on a point source as seen in Figure 2. In an infinite, adiabatic atmosphere, the ideal plume will be axisymmetric and stretch vertically to a point where the buoyancy force is no longer strong enough to counteract the viscous drag. A temperature inversion can form under certain atmospheric conditions, effectively trapping a rising smoke plume, preventing its vertical movement, and forcing it to diffuse laterally at that height [8].

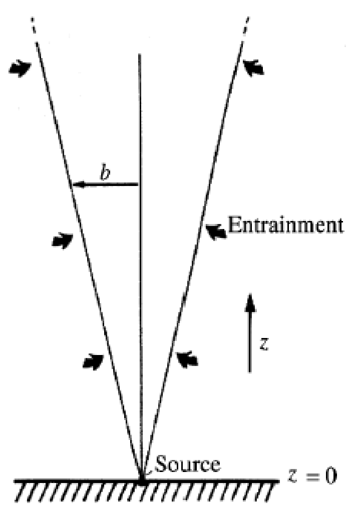

Figure 2 The buoyant plume from a point source [8].

The majority of plume correlations are based on the assumption that the fire is a point source.

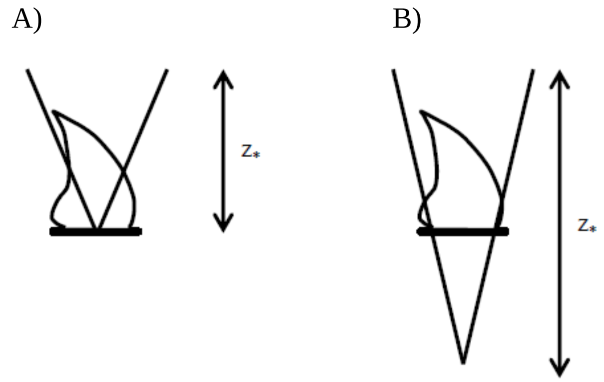

Figure 3 Principal sketch of point source A) general model B) Heskestad´s model [19].

When a fire has a larger base area, that is not a point source, the elevation of the heat source must be adjusted to account for some changes in order to properly calculate the plume as a point source [20]. The properties that need to be evaluated to account for the changes mentioned, is the area of the fire source and energy release rate. When this is accounted for it needs to be established if the flame will reach the smoke layer. Figure 3 illustrates the general model of a point source and the Heskestad's model which have taken in account for the changes needed [19].

Figure 4 illustrates a buoyant plume from a real fire source which interacts with a ceiling. Virtual origin, denoted Z_0, are dependent of the fire sources diameter and the total energy released. The virtual origin can lay beneath the fuel source and may be negative or above being positive, depending on the size of the fuel source. This indicate that the area of the fuel source is larger when comparing it to the energy released over the given area.

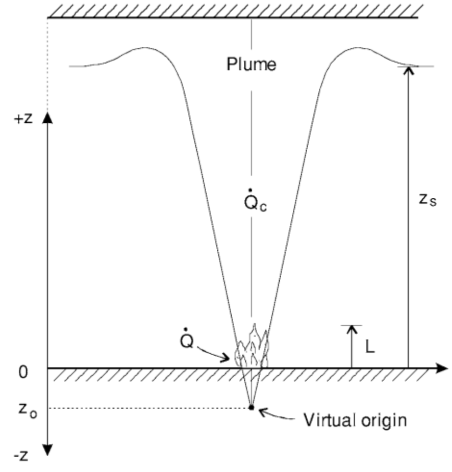

Figure 4 Buoyant plume from a real fire source where plume properties are shown. [7]

2.5 Flame height

2.5.1 Definition flame height

Mean flame height, denoted L, is defined where the flame will appear 50 % of the time. It is difficult to establish an equation to calculate the mean flame height that are derived from first principles, because of the turbulent behavior of the flame. To define the mean flame height the graph in Figure 5 is generally used. On the vertical axis, the intermittency, denoted I, is seen, with a value of 1 indicating the presence of a flame at all times. The distance above the fire source, z, is shown on the horizontal axis. The mean flame height, L, is defined as the height at which the intermittency is 0.5, that is, the height at which the flame appears half the time [7].

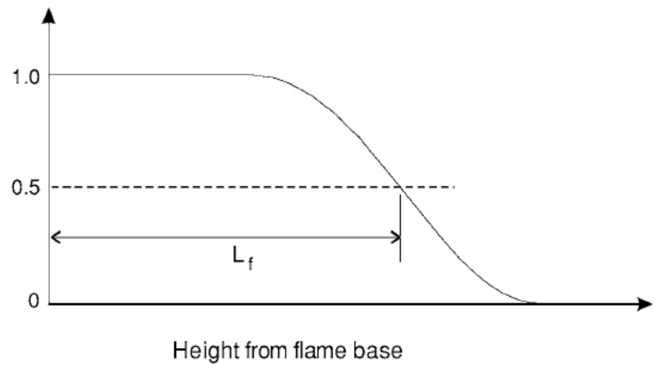

Figure 5 Definition of mean flame height [7]

To find the mean flame height an experimental procedure is needed. This procedure normally includes video equipment to document the flame height, this is because of the fluctuation (intermittent) in the upper part of the flame. The mean flame height can be calculated as followed [1]:

$$L = 0.235\dot{Q}^{2/5} - 1.02D \qquad \text{Eq. 8}$$

Eq. 8 is proposed by Heskestad and gives the mean flame height as a function of total energy release rate and diameter, where the energy release rate is given in kilowatts (kW) and the diameter of the fire source is given in meters (m), and gives a mean flame height in meters (m) [7].

2.5.2 Flame height correlations

Because of the turbulent nature of the flames, engineering equations for flame height derived from first principles is not possible, so investigation of the properties that influence the flame height is needed, in addition the use experimental data to express the flame height in terms of the dominating properties. In hydraulics, the nondimensional Froude number, denoted Fr, is used to describe liquid flows, also roughly applicable to the high-temperature gas in flames [7].

$$Fr = \frac{u^2}{gD} \qquad \text{Eq. 9}$$

where u is the flow velocity, g is the gravity acceleration, and D is the flow source's diameter. The denominator is proportional to gravity or buoyancy, while the numerator is proportional to momentum. $\dot{Q} = \dot{m}\Delta H_c$, where $\dot{m}$ is the burning rate and ΔH_c is the heat of combustion, can be used to express the Froude number in terms of energy release rate. Furthermore, the burning rate can be expressed as $\dot{m} = u\rho A$, where u is the gas velocity, A is the area of the fuel source, and ρ is the gas density (directly related to D^2). Because of the relationship between the Froude number, the energy release rate, and the diameter of the source the Froud number can be expressed as followed [7]:

$$Fr \propto \frac{\dot{Q}^2}{D^5} \qquad \text{Eq. 10}$$

It has been established that the geometry of turbulent diffusion flames scales with the square root of the Froude number. So, by representing the flame geometry as the flame height normalized by the source diameter, denoted L/D, it can be expressed as

$$\sqrt{Fr} \propto \frac{L}{D} \propto \sqrt{\frac{\dot{Q}^2}{D^5}} \propto \frac{\dot{Q}}{D^{5/2}} \qquad \text{Eq. 11}$$

Flame heights have been studied in relation to energy release rate and source diameter in a large number of studies [7]. The data has been expressed in terms of a nondimensional energy release rate, denoted $\dot{Q}^*$, which is given by the expression given in Eq. 3 [1]:

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{gD} D^2}$$

Where $\dot{Q}$ is the heat release rate, D is the equivalent fire diameter, and ρ_∞, c_p, and T_∞ refers to the ambient air properties. This dimensionless energy release rate parameter, which is the square root of the Froude number, has been discovered to be very important in controlling the geometry of fire plumes. When looking at the above equation when considering a large range of Froud numbers, that it is possible to express flame height as a function of diameter and energy release rate [7, 21].

$(\dot{Q}^*)^{2/5}$ for natural fires ranges from approximately 0.1-10 [22]. In Figure 6 a great number of experimental results are represented, where the mean flame height is normalized by source diameter, denoted L/D, and plotted against the dimensionless energy release rate, denoted $\dot{Q}^*$. The fires on the left side of the plot have a diameter of the same order as the flame height and a low Froude number, indicating buoyancy-dominated flows. Buoyancy is also dominant at intermediate Froude numbers. By looking at the upper right side of Figure 6 the high Froud number, high momentum jet flame regime is represented. But, as mentioned in natural fires $(\dot{Q}^*)^{2/5}$ ranges up to 10, and for most medium fires less than 2, and this is shown in the left-hand side of Figure 6 [7].

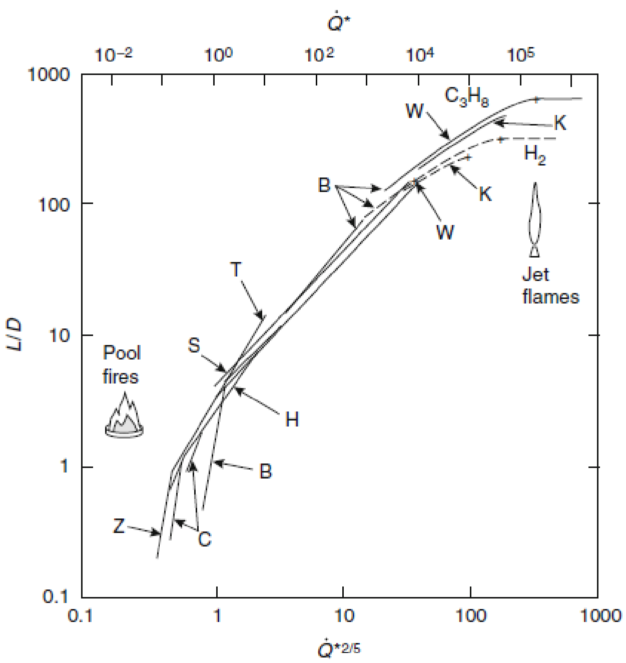

Figure 6 Flame height correlations compiled by McCaffrey (Normalized flame height vs. dimensionless energy release rate). Capital letters without subscripts correspond to various researchers as followed: B Becker and Liang, C Cox and Chitty, H Heskestad, K Kalghatgi, S Steward, T Thomas, W Hawthorne, and Z Zukoski. Capital letters with subscripts represent chemical formulae. [1]

The straight lines in Figure 6 indicates that the normalized mean flame height, L/D, correlates well with $\dot{Q}^*$ over a wide range of values. An equation presented by Heskestad gives good results for different regimes, except for jet flame regimes. The equation expresses mean flame height divided by diameter, and are as followed [7]:

$$\frac{L}{D} = 3.7\dot{Q}^{*2/5} - 1.02 \qquad \text{Eq. 12}$$

Eq. 12 maintains the relationship between the 2/5 power of $\dot{Q}^*$ over the large intermediate regime while exhibiting an increasing slope at small $\dot{Q}^*$, as seen in Eq. 12. A more convenient form of Eq. 12 gives the mean flame height as a function of energy release rate and diameter and is presented in chapter 2.5.1 as Eq. 8 [7].

2.6 Boundary surfaces

There are no physical barriers to limit vertical movement or restrict air entrainment across the plume boundary in an unconfined axisymmetric plume, however the fire plume can be impacted by surrounding surfaces in a confined environment. As a result, if there is a fire against a wall, the area through which air may be entrained is reduced (see Figure 7) [8].

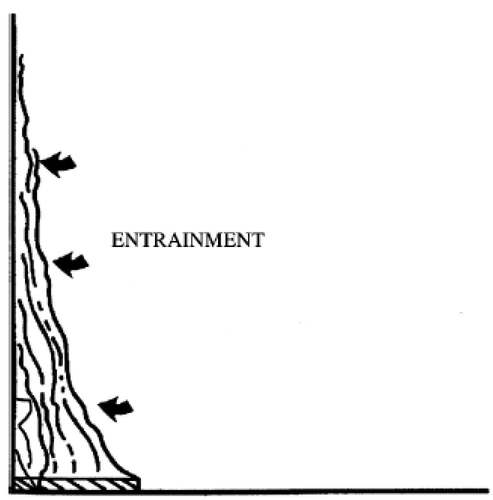

Figure 7 Interaction of a flame with a vertical surface [8]

There have been done relatively few measurements of the effect on flame height, and it was assumed that the flame would be taller than for an equivalent fire plume burning in the open. There was made a simple model that was used to estimate the flame height which involved an imaginary mirror image fire source as seen in Figure 8. This assumption presumed that the size of the fire next to a wall would double in size, meaning it would be equal to the actual and imaginary fire source in the open (illustrated with square pan in Figure 10) [8]. Hasemi and Tokunaga found evidence that it was not the case for experimental gas fires, the result indicated that the conventional imaginary fire source method did not hold for fire plumes against a wall, their result was less than the size of the actual fire source and mirror would be combined [3].

McCaffery has reviewed effects on flame height of placing fire sources next to a wall or in a corner, which refers to experiments conducted by Hasemi and Tokunaga [3]. The effects are generally reported to be small [1].

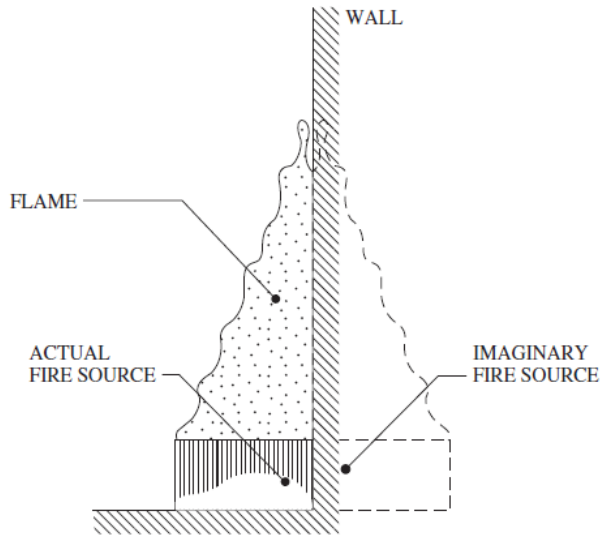

Figure 8 Concept of the imaginary fire source [8]

As seen in Figure 9 the resulting restriction on free air entrainment have a significant effect if the fire is placed close to a wall or in a corner which is formed by the intersection of two walls. The same three regimes presented by McCaffery (Figure 1) are observed, but in the buoyant plume the temperature decreases more slowly with height as the rate of mixing with ambient air will be less than the unbounded case [8].

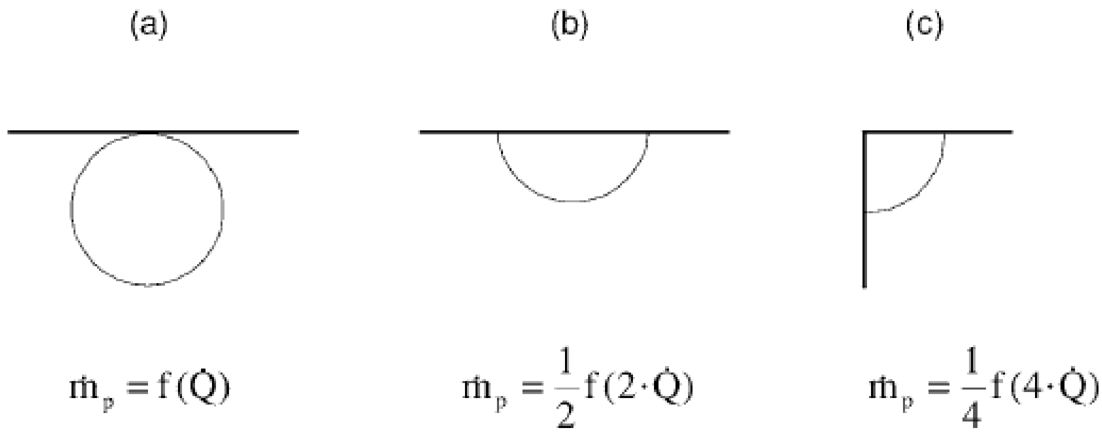

Figure 9 Plane view of a fire: (a) free burning; (b) burning against a wall: and (c) burning in a corner [7].

The presents of a side wall near a plume's source can have a significant impact on the plume's entrainment rate and other properties. Sargent and Cetegen [23] suggested that the interaction of an axisymmetric plume with a vertical wall or a corner could be emulated by using a reflection principle. This principle assumes that an axisymmetric plume source placed next to a vertical surface can be viewed as half of a plume which has a source with twice the heat release rate, and a plume placed in a corner with a quarter plume rising from a source with four times its heat release rate, see figure 10. There have been done experimental work showing that, when a circular burner was placed with one edge tangent to a vertical wall as shown in Figure 9(a) the plume developed as an axisymmetric plume, and flame attachment to the wall would not occur. Because the air entrainment into the circular fire source was not blocked by the wall the plume geometry and entrainment rate were not strongly affected by the presence of the wall. Further in Figure 9(b) illustrates a semi-circular burner placed with it straight edge against a wall where 50 % of area for air entrainment was removed. The plume was attached to the wall and developed as a half plume with flame height and entrainment rate closely approximating those for a full circular burner with twice the energy release rate. After placing the semi-circular fire source against the wall, a quarter-round burner was placed in a corner, leaving no gap between the burner and the two walls. The plume attached to both walls and developed as if it were one quarter of the plume rising above a circular burner with four times the energy release rate [23].

Zukoski’s simple plume mass flow equations are an approximation and can be used to develop a relationship for the cases in Figure 9. Zukoski plume mass flow equation for a wall can be written as [23]:

$$\dot{m}_{p,wall} = \frac{1}{2}0.071(2\dot{Q})^{1/3}z^{5/3}$$

Which simplifies to

$$\dot{m}_{p,wall} = 0.045\dot{Q}^{1/3}z^{5/3}$$

Where a factor 2 is presented to use when calculating the relationship with a wall.
For corner, the plume mass flow is roughly one quarter of the flow from the unbounded fire with four times the energy release rate, so, the Zukoski plume mass flow equation for corner can be written as:

$$\dot{m}_{p,wall} = \frac{1}{4}0.071(4\dot{Q})^{1/3}z^{5/3}$$

Which simplifies to

$$\dot{m}_{p,wall} = 0.028\dot{Q}^{1/3}z^{5/3}$$

Where *z* is the height of the elevated layer above the base of the fire and is given in meter, and a factor 4 is presented to use when calculating the relationship with a corner. These effects of the wall and corner burning geometries can be treated as illustrated in Figure 10 [24].

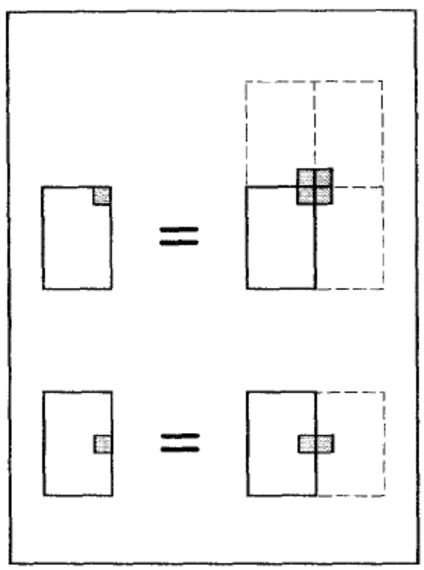

Figure 10 Effect of burning location. Top shows equivalent corner geometry: bottom shows equivalent wall geometry. Shaded box indicates one unit of burner heat output [24].

Williamson conducted tests with a burner flush in a corner, 5 cm from the corner, and 10 cm from the corner. The flame did not attach to the wall at those relatively short stand-off distances. This demonstrates that the fuel source does not need to be moved far from the wall or corners to exhibit plume properties in the flame region. Because less air is entrained, and the fuel must travel a longer distance to get fully combusted, the mean flame heights for wall and corner will be higher than in an unbound asymmetrical plume [7, 18].

Takahashi and Tanaka did an experimental study on the relationship between air entrainment and flame/plume behavior when a fire source was placed in and near a corner in different sizes [25]. The results showed a decrease in turbulence and increase in flame height the closer the pan was placed to the corner as seen in Figure 11. It is stated that the flame height is approximately twice as large compared to free boundary conditions [25].

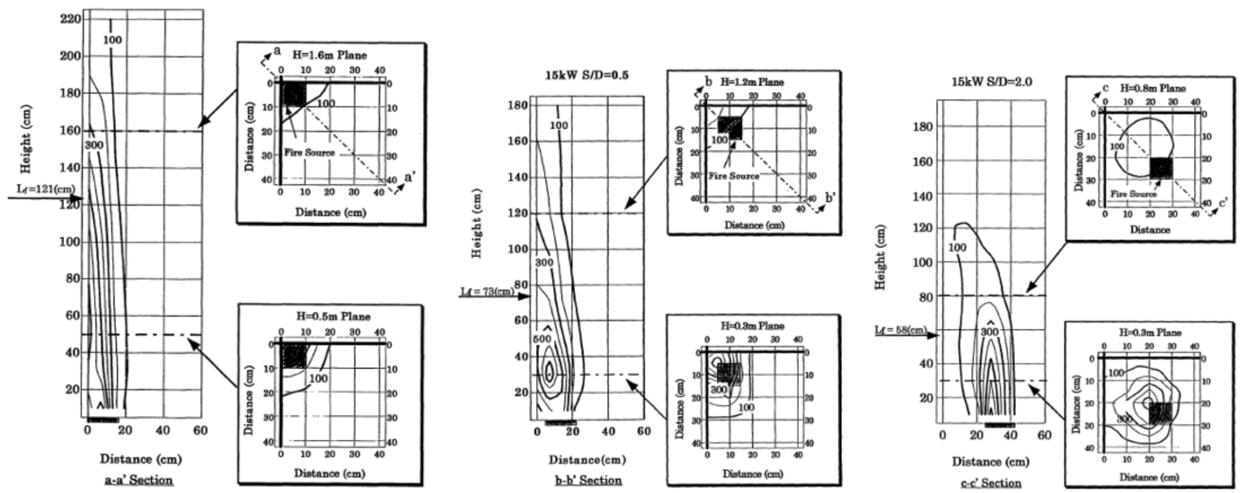

Figure 11 Isothermal contour for vertical section of 45 angle from each wall and horizontal plans of above and below the mean flame height. A) flush to a corner B) 5 cm from a corner C) 20 cm from a corner [25].

3 Method

This chapter contain the description of the experiments, and procedure of carrying out the experiments.

3.1 Experimental set-up

In the current experiments, flame height as a function of heat release rate and boundary conditions will be investigated. Propane and heptane will be used as fuels since they represent gaseous and liquid fuel types. In Table 1 the properties for the fuel used for the experiments are presented.

Table 1 Fuel properties

Fuel	Chemical formula	ΔH_c [MJ/kg]	$\dot{m}''_\infty$ [kg/m^{2}s]	Density [kg/m^3]	$k\beta$ [m^{-1}]
Propane	C_3H_8	46	0.099	585	1.4
Heptane	C_7H_{16}	44.6	0.101	675	1.1

In these experiments three different boundaries will be investigated, both in small- and medium-scale configurations. The small-scale experiments were executed in a smaller fire lab located at the Western Norway University of applied Science in Haugesund and the medium-scale experiments were conducted at the fire lab at RESQ located in Bleivik close to Haugesund. The experiments were executed inside where the flames were not exposed to outer factors, such as wind. The fire labs are equipped with large venting systems to remove the smoke produced during the different experiments.

For the experiments conducted, there were three different boundaries. For the one- and two-sided boundary the wall used was made of incombustible material (scamotec 225). The height of the walls for small- and medium-scale was 1.2 m and 2.4 m. For all experiments, square pans in four different sizes were used. P-1 and P-2 are used for the propane fire and P-3 and P-4 are used for heptane fires, see Table 2. The pans were placed on gypsum foundation to make sure that they were horizontal.

Table 2 Size of the pans used for the experiments. P-1 and P-2 are used for propane, and P-3 and P-4 are used for heptane

Pan number	Area of the pan [m^2]	Equivalent diameter [m]	Depth [cm]
P-1	0.022	0.169	10
P-2	0.30	0.618	25
P-3	0.09	0.338	10
P-4	0.019	0.158	10

To measure the flame height, two graduated rulers was placed on each side of the pan. The graduated rulers are placed so that the zero point is from the top of the pan (see Figure 13 - Figure 15 and Figure 17 - Figure 19 for the placement of the graduated ruler). A camera is set to take 99 photos to document the fire. For some of the experiments the camera was angled slightly to the right, which mean the average height of the flame from the two graduated ruler needs to be calculated to get the right height after the experiments are conducted.

3.1.1 Other equipment

The thermocouples were attached to a computer which registered the temperature during every experiment (Figure 12).

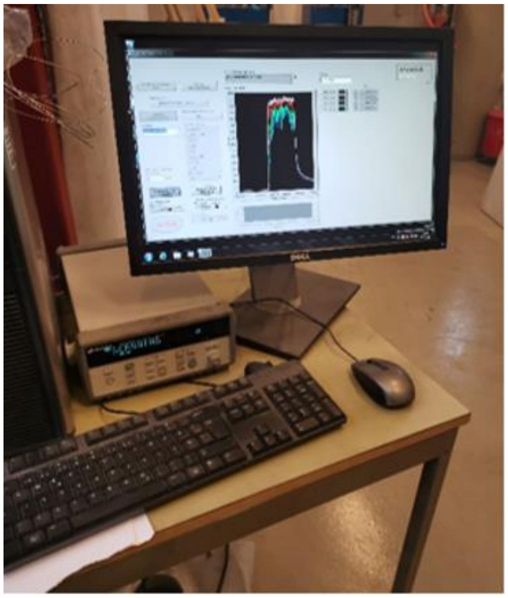

Figure 12 Computer that registered the temperature

The temperature was measured with thermocouples, where the thermocouple was placed along the center line of the fire for all configurations, and approximately 1 cm from the wall for one- and two-sided boundary. There were placed four thermocouples for small-scale fires and five thermocouples for medium-scale fires. This was to document the temperature to indicate the flame height and compare the temperature with photos to estimate where the flame is 50 % of the time, called mean flame height. The height placement can be seen in Table 3, and in Figure 13 - Figure 19.

Table 3 Placement of the thermocouples for the open, next to wall and corner fire. Remark: For the fire next to wall and corner the thermocouples were placed 1 cm out from the incombustible wall, while the placement of the thermocouples for the open fire was located along the centre of the pan

Channel	Small-scale [cm]	Medium scale [cm]
1	40	120
2	50	145
3	60	170
4	70	195
5	-	220

3.1.2 Experimental set-up for propane fire

In Table 4 the energy release rate for the two set-ups and configurations using propane is given.

Table 4 Energy release rate for propane for the different set-ups

	Small-scale	Medium scale	
	Q [kW]	Q [kW]	Q [kW]
Open flame	17.5	76.2	114.2
One-sided boundary surface	17.5	76.2	114.2
Two-sided boundary surface	17.5	76.2	114.2

The pans used for propane was filled with piping to evenly distribute the propane, different layers of bricks, open-meshed material, and sand are used to let the propane flow evenly to the surface of the pan, ensuring a steady state fire. A gas detector was placed near the floor to detect if a leakage occurred. After placing the pan used for propane for small- and medium-scale fires, the hose that transport the propane from the tank is attached to the pan, this is the same for all configurations (free burn, one- and two-sided boundary surface).

The propane is stored in liquid form in small tanks for small-scale experiments at HVL and a large container at RESQ (for medium-scale fire). The tank is installed with a valve on the upper side of the tank,

and when the valve opens the liquid gas gets exposed to normal atmospheric pressure and temperature resulting the liquid to vaporize. The propane gas was distributed with a gas pressure regulator which was connected to the pan, the regulator was controlled using computer program. There were conducted 9 small scale experiments and 30 medium scale experiments using propane gas, 9 experiments with 0.40 g/s, 15 with a gas flow at 1.65 g/s and 15 experiments with 2.47 g/s, giving HRR of 18, 76 and 114 kW.
Figure 13 shows the experimental set-up for the open fire configuration using propane, where the pan is placed approximately 1-2 meters from the closest wall depending on the size of the experiment. In Figure 14 and Figure 15 the configuration for one- and two-sided boundary is shown. The pan for these configurations is flush with the boundaries, meaning no air will be entrained between the walls and the pan.

A) B)

Figure 13 Experimental set-up for propane fire for free burn A) small-scale: pan is placed approximately 1 meter from the closest wall B) medium scale: pan is placed approximately 2 meters from the closest wall

A) B)

Figure 14 Experimental set-up for propane fire for one-sided boundary A) small-scale B) medium scale

A) B)

Figure 15 Experimental set-up for propane fire for two-sided boundary A) small-scale B) medium scale

3.1.3 Experimental set-up for heptane

For the heptane fires the pans was filled with water, P-3 was filled with 6.05 l of water and P-4 was filled with 1 l of water, leaving space for the heptane to be poured in the pan (see Table 5). To get the right amount of heptane and water in the pan a weight scale was used and tared between every experiment. The measuring cups was used to pore water and heptane in the pan, see Figure 16.

Figure 16 Weight scale used to measure the amount of heptane needed and the measuring cups used to measure the amount of water and pour the liquid in the pan.

Table 5 Content of the pan for the execution of the experiments using heptane

Pan number	Area of the pan [m^2]	Amount of heptane [g]	Amount of water [l]
P-3	0.019	100	1.00
P-4	0.09	1350	6.05

After conducting the medium scale experiments using propane, the plan was to use the same sized pan to conduct the experiments using heptane. When calculating the mean flame height using Eq. 8 for P-2 with a diameter 0.618 m the calculated flame height was 2.1 m. Before the execution of the experiments, it was assumed that the mean flame height for one- and two-sided boundary would increase. Since the material, the walls were made of only reach 2.2 m, the size of the pan was considered to be too large. So, by decreasing the size of the pan for heptane there was no need to increase the height of the two boundaries. When using P-4 with a diameter 0.338 m the calculated flame height was 1.065 m for open fire.
There were conducted 9 experiments for small-scale and 15 experiments for medium scale, using heptane as a fuel.

Figure 17 shows the experimental set-up for the open fire configuration using heptane, where the pan is placed approximately 1-2 meters from the closest wall depending on the size of the experiment. In Figure 18 and Figure 19 the configuration for one- and two-sided boundary is shown. The pan for these configurations is flush with the boundaries, meaning no air will be entrained between the walls and the pan.

A) B)

Figure 17 Experimental set-up for heptane fire for free burn A) small-scale: pan is placed approximately 1 meter from the closest wall B) medium scale: pan is placed approximately 2 meters from the closest wall.

A) B)

Figure 18 Experimental set-up for heptane fire for one-sided boundary A) small-scale B) medium scale

A) B)

Figure 19 Experimental set-up for heptane fire for one-sided boundary A) small-scale B) medium scale

3.2 Procedure

For the experiments, a procedure was made to perform all experiments equally. There were made two different procedures to account for the two fuels, as shown in Table 6.

Table 6 Procedure used for experiments containing propane and heptane.

	Propane	Heptane
1	Turn on the two computers and start the programs that control the gas and the thermocouple measurement	Turn on the computer and start the programs that control the thermocouple
2	Fill in the details of each experiment on the SJA checklist made for the execution of the experiments	Fill in the details of each experiment on the SJA checklist made for the execution
3	Lit the pan with a low gas fire	Turn on the data logger for the thermocouple measurement
4	Turn on the thermocouple measurement	Pour the amount of water needed in the pan and change it between every experiment.
5	Check if the camera is set correctly and adjust the camera to 99 photos.	Reset scale, place a bucket on the scale and pour the heptane in the pan.
6	After ca 1 minute when the flame has burned with the given amount of gas and the flames have stabilized, start the camera. (Experiment will last ca. 2 minutes)	Ignite the heptane at the same time as the timer starts.
7	When the camera has stopped taking photos, adjust the gas controller to ca 1 gram/second to maintain the fire between experiments.	After ca 1 minute when the flame has burned and the flames have stabilized, start the camera, and take 99 photos
8	Turn off the thermocouple measurement	When the heptane has burned out stop the thermocouple measurement and the timer
9	Turn on ventilation fan to vent out all the smoke.	Turn off the thermocouple measurement
10	Before the experiment can start, close the gates and the ventilation fan.	Turn on ventilation fan to vent out all the smoke.
11		Before the experiment can start, close the gates or the ventilation fan.

4 Results

To determine where the mean flame height is for each of the current experiment, each picture of the 99 photos from each experiment is gone through and each instantaneous flame height is determined, see Figure 22 to Figure 25 for propane and Figure 27 to Figure 29 for heptane. The average of instantaneous flame height is then calculated giving the mean flame height. The pictures where detached flames are observed above the flame were taken in consideration when analyzing the pictures for each of the current experiments, but the detached part is not included in the measurements. The mean flame height for the three configurations is illustrated with a red line in chapter 4.2 and 4.3.

4.1 Estimating the flame height

The flame height in each photo was estimated by inspection of the flame. To estimate the mean flame height the turbulent eddies in the flame structure were visually observed for the different set-ups.
The flame height was determined where the flame was obvious eminent, because of the behavior of the flames for the different configurations, as seen in Figure 20. The part where the flame was starting shedding and considered not a part of the main flame, was not taken in consideration when determine the flame height. The same evaluation of the flame height was made for free burn, one-sided boundary surface and two-sided boundary surface. Blue arrows show the part of the flame that is not taken in consideration. The blue circles are the detached flame and in previous research photos that showed these kinds of flames was removed and not taken in consideration [26].

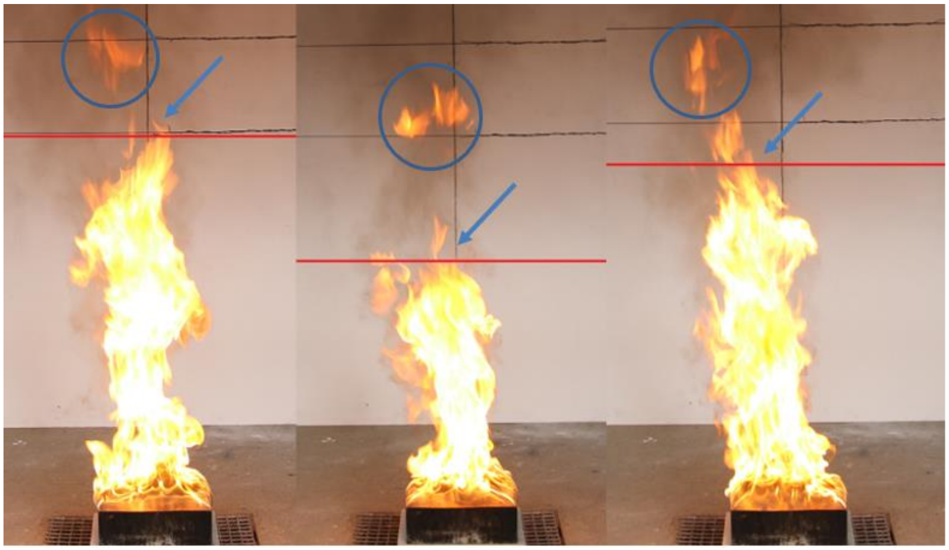

Figure 20 Example of pictures from one of the experiments conducted in the open where the instantaneous flame height is marked with a red line. The detachment part is not included in the flame height. The flame height is estimated where main body of the flame is present, and shedding begins.

4.2 Propane

Experiments were conducted with propane fires of 18 kW for the small-scale fires, and 76 kW and 114 kW for medium-scale fires for all three configurations. The gas flow was held steady for up to three minutes per experiment, where the first minute after the given flow was set, was to make sure the flame was as stable as it could be, while the remaining two minutes were used to take photos. The mean height for the experiments conducted using propane are presented in Table 7 and Table 8, and show the mean flame height after combining the flame height for all experiments for each of the given gas flow.

Table 7 Mean flame height results for small-scale experiments using propane given in meters.

	Open	Wall	Corner
	17.5 kW	17.5 kW	17.5 kW
1	0.513	0.603	0.740
2	0.560	0.637	0.726
3	0.545	0.638	0.746
Average L	0.539	0.626	0.737
L/D	3.186	3.699	4.356

Table 8 Mean flame height results for medium-scale experiments using propane given in meters.

	Open		Wall		Corner	
	76 kW	114 kW	76 kW	114 kW	76 kW	114 kW
1	0.742	0.934	0.754	0.869	1.061	1.248
2	0.661	0.812	0.761	0.969	1.083	1.267
3	0.646	0.927	0.722	0.862	1.024	1.291
4	0.702	0.928	0.753	0.975	0.998	1.287
5	0.659	0.971	0.772	1.027	1.074	1.241
Average L	0.682	0.914	0.752	0.940	1.048	1.267
L/D	1.099	1.473	1.212	1.515	1.689	2.041

4.2.1 Open fire

As mentioned, the small-scale experiments were conducted in a different fire lab located at HVL Haugesund. Here the set-ups were placed under the venting system that needed to be operational during the experiments, this could have an impact on the flame, and will be discussed further in chapter 5. Figure 21 illustrates the mean flame height for small-scale fires giving a mean flame height 0.54 m for 18 kW fire. Figure 22 illustrates the mean flame height for medium scale fires of 76 kW and 114 kW giving mean flame heights of 0.68 m and 0.91 m.

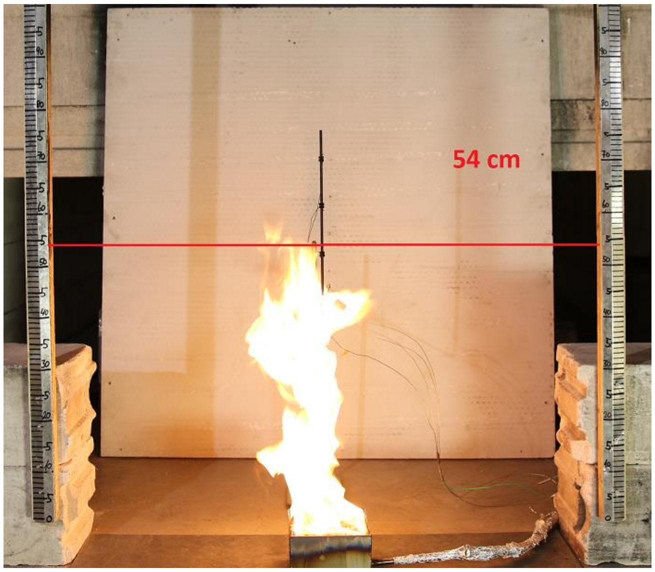

Figure 21 Open mean flame height for small-scale propane fires for 18 kW.

A) B)

Figure 22 Open mean flame height for medium scale propane fires for A) 76 kW and B) 114 kW.

4.2.2 One-sided boundary fire

The mean flame height for the small-scale experiments conducted for one-sided boundary is illustrated in Figure 23 where the mean flame height is 0.63 m for 18 kW fire. Figure 24 illustrates the mean flame heights for medium scale fires of 76 kW and 114 kW, giving mean flame heights of 0.75 m and 0.94 m.

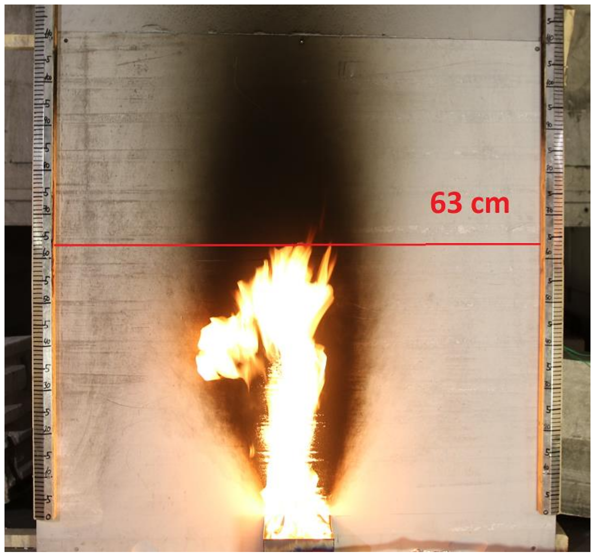

Figure 23 One sided boundary surface fire for small scale propane fires for 18 kW.

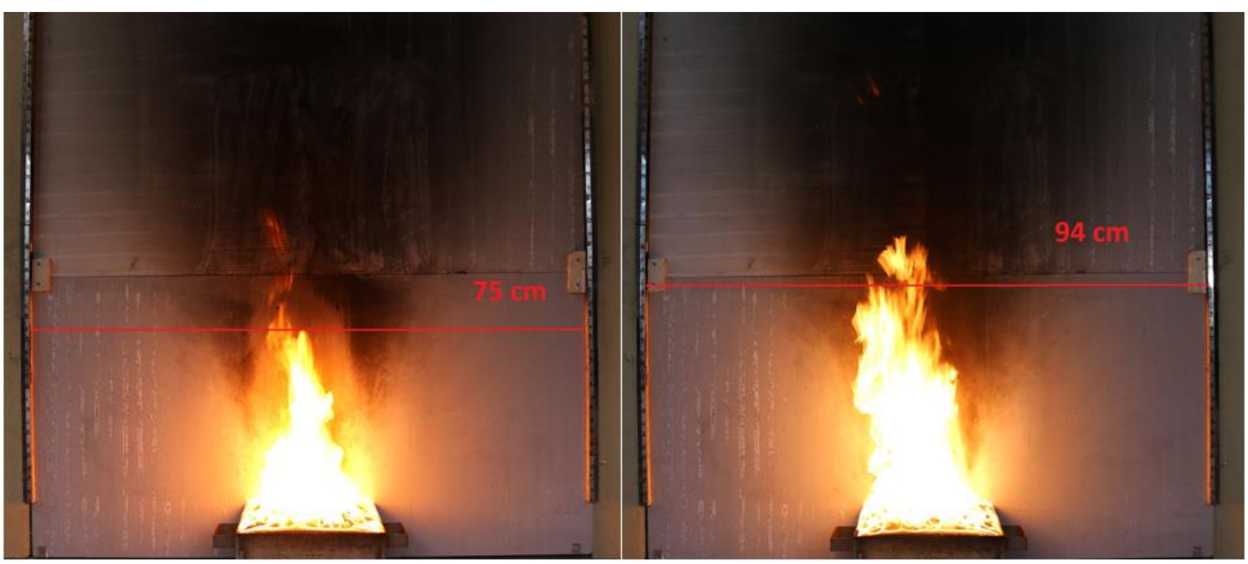

Figure 24 One sided boundary surface fire for medium scale propane fires for A) 76 kW and B) 114 kW.

4.2.3 Two-sided boundary surface fire

The mean flame height for small-scale experiments conducted for two-sided boundary is illustrated in Figure 25 where the mean flame height is 0.74 m for 18 kW fire. Figure 26 illustrates the mean flame height for medium scale for 67 kW and 114 kW fires and gave a mean flame height 1.05 m and 1.27 m.

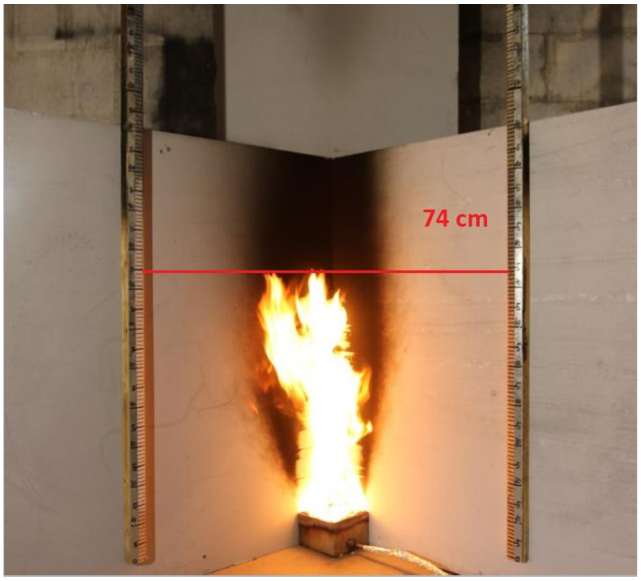

Figure 25 Two-sided boundary surface fire for small scale propane fires for 17.5 kW.

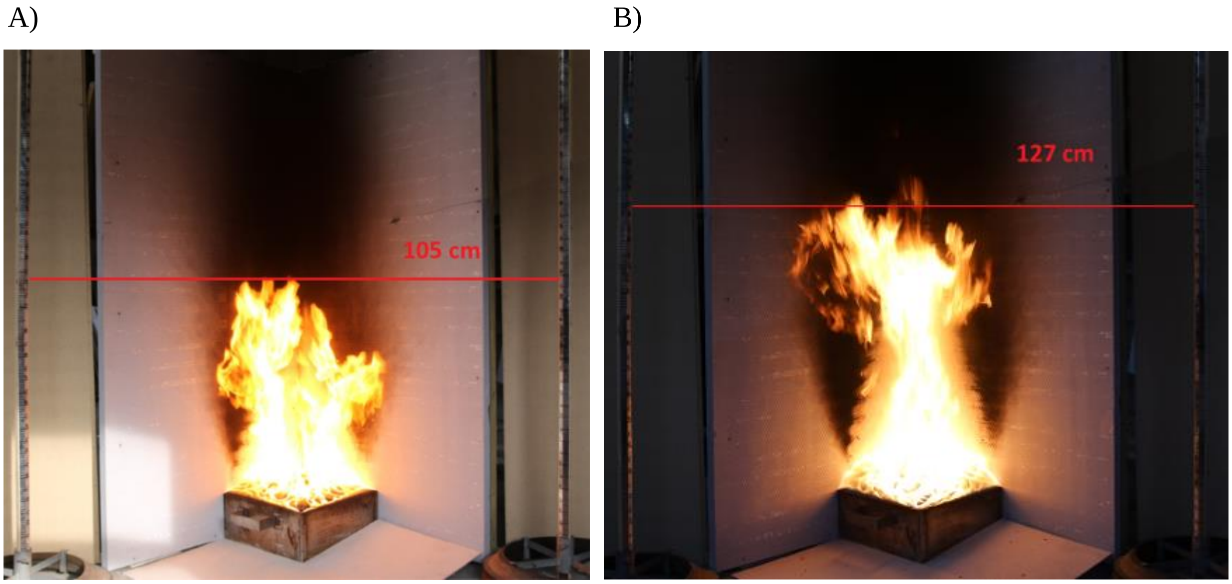

Figure 26 Two-sided boundary surface fire for medium scale propane fires for A) 76 kW and B) 114 kW.

4.3 Heptane

For the experiments using heptane as a fuel, the energy release rate had a different outcome than for propane, the energy release rate for propane was pre-determined and controlled by a gas flow controller, but for heptane the energy release rate was calculated as the average for each experiment conducted using Eq. 5. Where mass loss rate was calculated by dividing the amount of fuel used by the time the fuel used to burn. The result for mass loss rate and energy release rate for small-scale and medium scale fires is shown in Table 9. When going through the photos for the fifth experiment for open fire (medium scale) the pictures were damaged by the sun that reflected from the window to the scale, so interpret the photos was not possible.

Table 9 Mass loss rate and energy release rate for each experiment conducted using heptane as a fuel.

	Open				Wall				Corner			
	Small-scale		Medium scale		Small-scale		Medium scale		Small-scale		Medium scale	
	$\dot{m}$ [g/s]	$\dot{Q}$ [kW]	$\dot{m}$ [g/s]	$\dot{Q}$ [kW]	$\dot{m}$ [g/s]	$\dot{Q}$ [kW]	$\dot{m}$ [g/s]	$\dot{Q}$ [kW]	$\dot{m}$ [g/s]	$\dot{Q}$ [kW]	$\dot{m}$ [g/s]	$\dot{Q}$ [kW]
1	0.202	6.294	2.437	76.073	0.207	6.449	2.706	84.487	0.265	8.259	3.595	112.246
2	0.204	6.371	2.476	77.300	0.207	6.470	2.680	83.660	0.261	8.151	3.578	111.713
3	0.203	6.332	2.639	82.381	0.211	6.572	2.679	83.640	0.269	8.409	3.589	112.060
4	-	-	2.368	73.914	-	-	2.695	84.144	-	-	3.618	112.968
5	-	-	-	-	-	-	2.704	84.438	-	-	3.654	114.068
avg	0.203		2.480		0.208		2.693		0.265		3.607	

The mean flame height for all experiments conducted is presented in Table 10 and Table 11, where Table 10 shows the mean flame height for small-scale experiments and Table 11 shows the mean flame height for medium-scale experiments. The average height for all experiments is calculated and given in each table.

Table 10 Mean flame height results for small-scale experiments using heptane given in meters

	Open	Wall	Corner
	[m]	[m]	[m]
1	0.387	0.468	0.734
2	0.401	0.492	0.782
3	0.401	0.503	0.771
Average L	0.396	0.488	0.762
Average L/D	2.548	3.135	4.900

Table 11 Mean flame height results for medium-scale experiments using heptane given in meters

	Open	One-sided (Wall)	Two-sided (Corner)
	[m]	[m]	[m]
1	0.910	1.232	1.278
2	1.080	1.241	1.365
3	0.983	1.233	1.722
4	0.964	1.216	1.761
5	-	1.222	1.774
Average	0.984	1.229	1.580
Average L/D	2.908	3.630	4.667

4.3.1 Open fire

The mean flame height for small- and medium scale experiments conducted for open fire is illustrated in Figure 27 where the mean flame height is 0.39 m (small-scale fire) and 0.98 m (medium scale).

A) B)

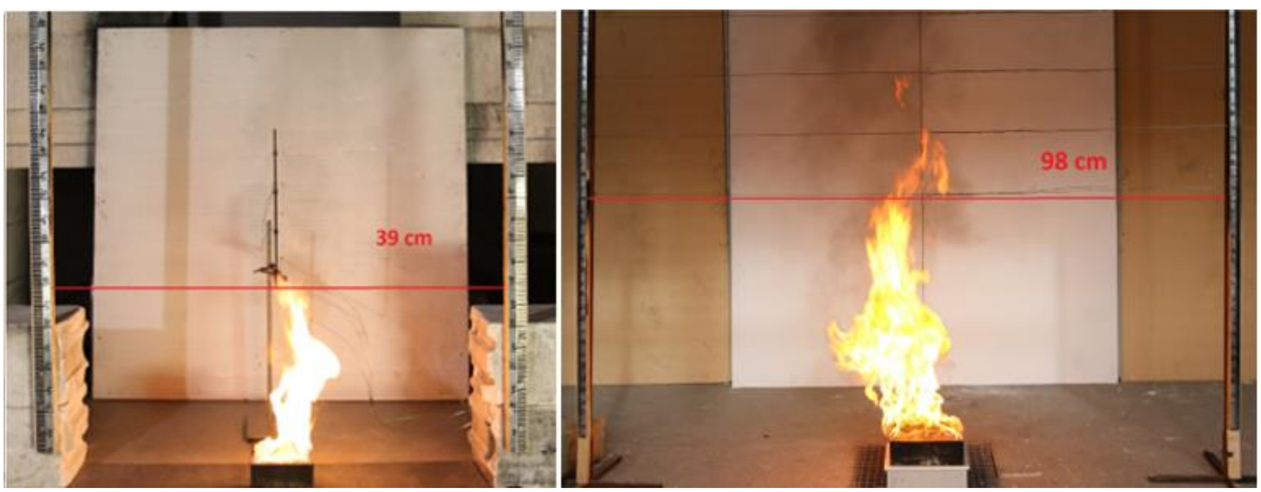

Figure 27 Mean flame height: Open fire for A) Small-scale fire and B) Medium scale using heptane.

4.3.2 One-sided boundary surface

The mean flame height for small- and medium scale experiments conducted for one-sided boundary is illustrated in Figure 28 where the mean flame height is 0.49 m (small-scale fire) and 1.23 m (medium scale).

A) B)

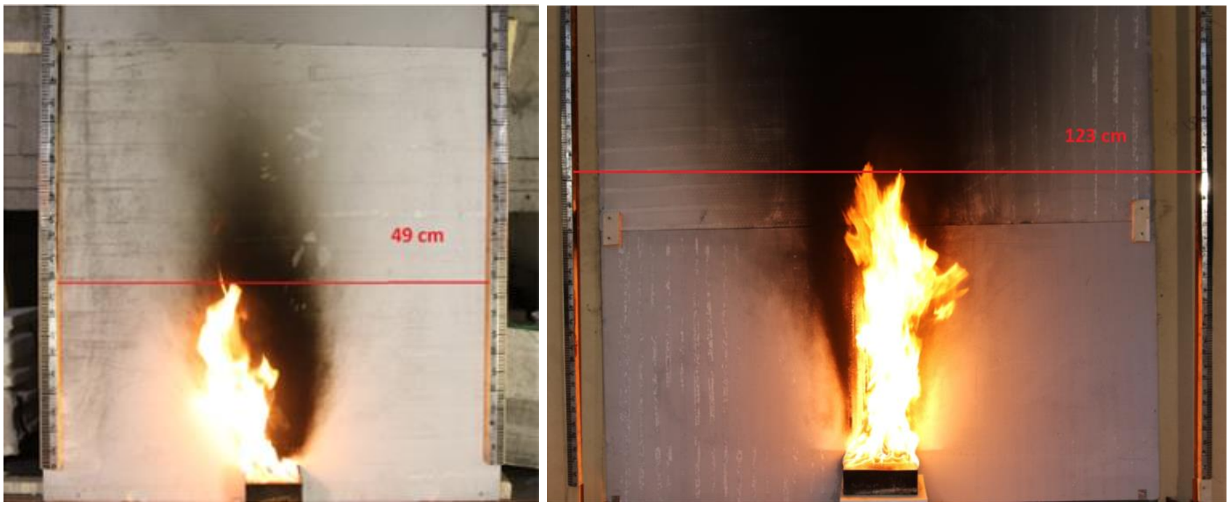

Figure 28 Mean flame height: one-sided boundary surface for A) Small-scale fire and B) Medium scale fire using heptane

4.3.3 Two-sided boundary surface

The mean flame height for small- and medium scale experiments conducted for one-sided boundary is illustrated in Figure 29 where the mean flame height is 0.76 m (small-scale fire) and 1.58 m (medium scale).

A) B)

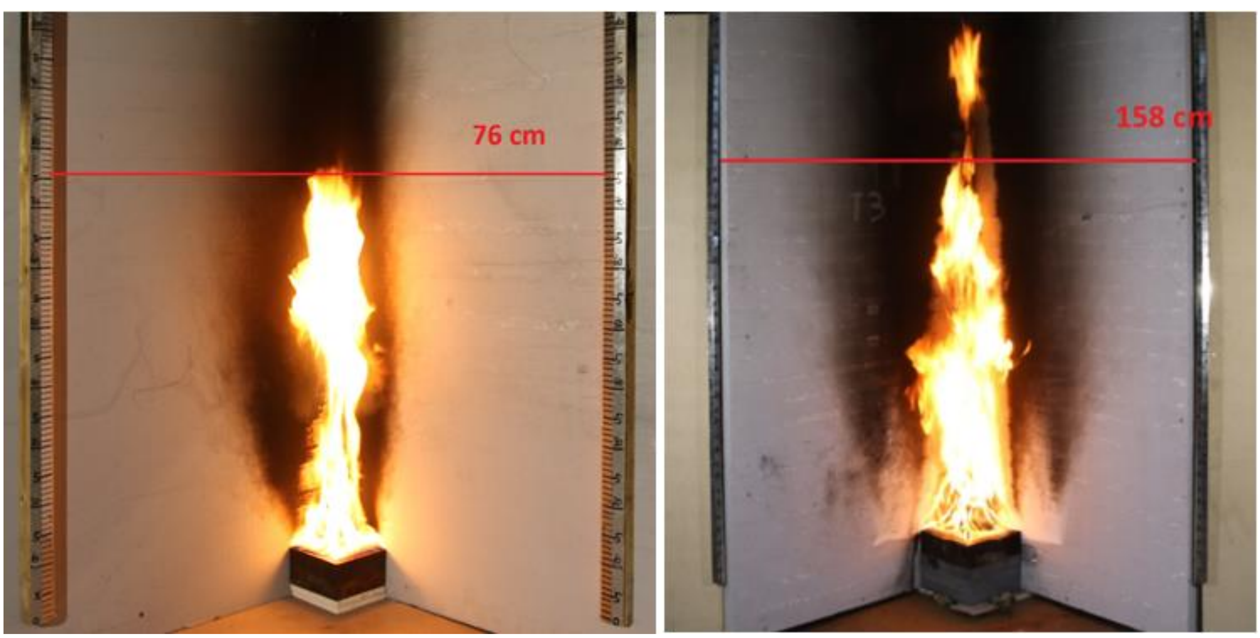

Figure 29 Mean flame height: two-sided boundary surface for A) Small-scale fire and B) Medium scale fire using heptane

4.4 Summary results

When observing the flames for the three set-ups the flames behaved inconsistent form each set-up, meaning some of the shedding of the flame happened closer to the fire source when placed to the one- and two-sided boundary causing a higher deviation between open fire and fire flushed to a boundary. Temperature was measured for each experiment to compare the flame height that was observed in a picture, but because of the inconsistent behavior of the flames the measurement of the temperature will not be used in this thesis.

In Table 12 and Table 13 the results from propane and heptane experiments are summarized and are the average value for all experiments conducted. In Table 12 the result for propane is presented for the two set-ups: Small- and medium-scale and the three configurations: open fire, one-and two-sided boundary. The table shows the energy release rate for propane is the same for each configuration when looking at the amount of fuel separately, this equals the same dimensionless energy release rate for each amount of fuel used for all three configurations.

In Table 13 the result for heptane is presented for the two set-ups that includes the three configurations: open fire, one- and two-sided boundary. The energy release rate and dimensionless energy release rate are different for each configuration as opposed to the experiments using propane.

Table 12 Summary of the average result for the two set-ups (medium- and small-scale) and the three configuration (open fire, one- and two-sided boundary) using Propane

	Small-scale				Medium scale							
Amount of fuel	0.40 g/s				1.65 g/s				2.47 g/s			
	$\dot{Q}$ [kW]	L [m]	$\dot{Q}^*$ [-]	L/D [-]	$\dot{Q}$ [kW]	L [m]	$\dot{Q}^*$ [-]	L/D [-]	$\dot{Q}$ [kW]	L [m]	$\dot{Q}^*$ [-]	L/D [-]
Open	17.5	0.5	1.4	3.2	76	0.7	0.2	1.1	114	0.9	0.3	1.5
Wall	17.5	0.6	1.4	3.7	76	0.8	0.2	1.2	114	0.9	0.3	1.5
Corner	17.5	0.7	1.4	4.4	76	1.0	0.2	1.7	114	1.3	0.3	2.0

Table 13 Summary of the result for the two set-ups (medium- and small-scale) and the three configurations (open fire, one- and two-sided boundary) Heptane

	Small-scale				Medium scale			
Amount of fuel	100 g				1350 g			
	$\dot{Q}$ [kW]	L [m]	$\dot{Q}^*$ [-]	L/D [-]	$\dot{Q}$ [kW]	L [m]	$\dot{Q}^*$ [-]	L/D [-]
Open	6.3	0.4	0.6	2.6	77.4	1.0	1.0	2.9
Wall	6.5	0.5	0.6	3.1	84.1	1.2	1.2	3.6
Corner	8.3	0.8	0.8	5.0	112.6	1.6	1.5	4.7

As shown in Table 7 – Table 8 for propane, and Table 10 – Table 11 for heptane the variation in flame height for each of the experiments conducted are quite small as illustrated in Figure 30 so the results containing error bars will not be used when presented in Figure 31 and Figure 32.

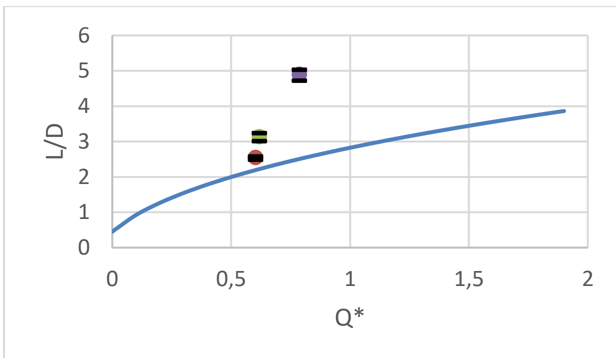

Figure 30 Dimensionless flame height as a function of dimensionless energy release rate for small-scale heptane fires where error bars are illustrated in black. Each of the three circular marks illustrates the average Dimensionless flame height as a function of dimensionless energy release rate for the three configurations.

A) B)

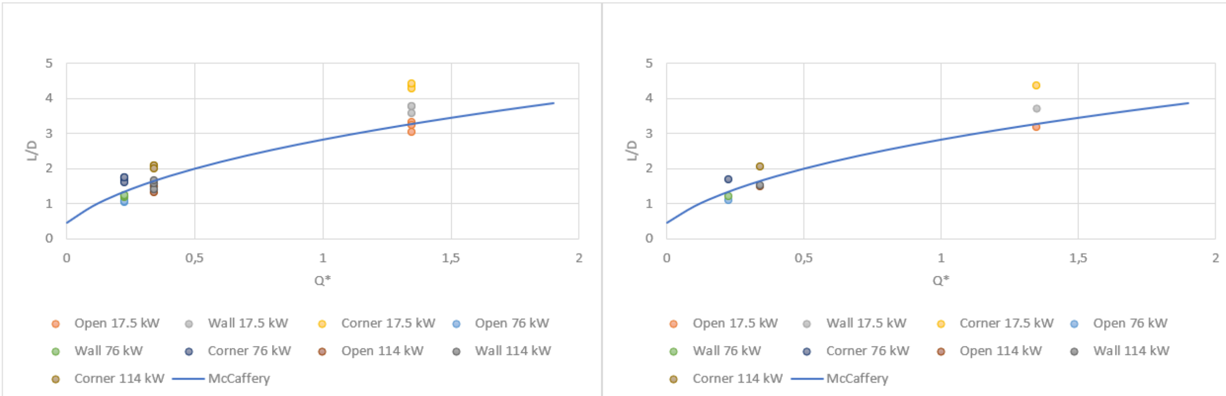

Figure 31 Dimensionless flame height, L/D, as a function of dimensionless energy release rate, $\dot{Q}^*$, for propane A) result from small- and medium-scale experiments for all configuration containing propane B) the average result from small- and medium-scale experiments for all configurations containing propane.

A) B)

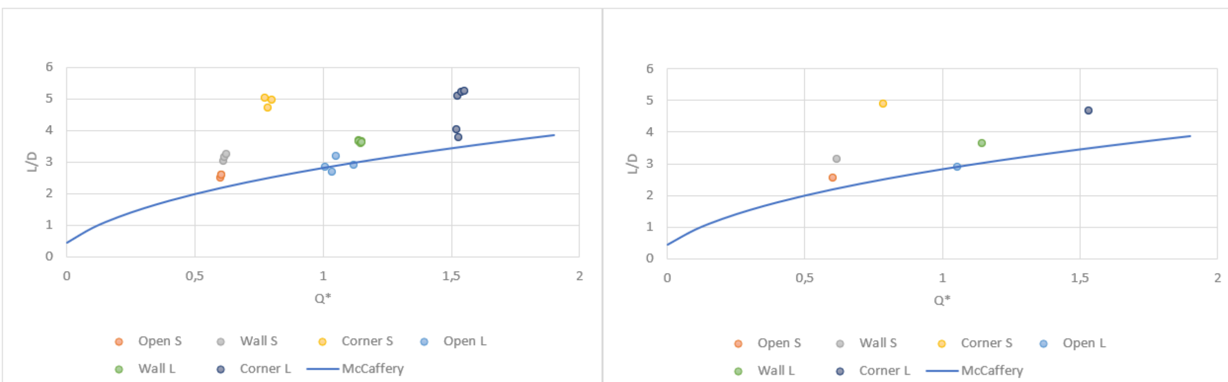

Figure 32 Dimensionless flame height, L/D, as a function of dimensionless energy release rate, $\dot{Q}^*$, for heptane A) result from small- and medium-scale experiments for all configuration containing heptane B) the average result from small- and medium-scale experiments for all configurations containing heptane.

By analysing the three boundaries, it shows there is a slightly difference between open fire and one-sided boundary fire, but a significant difference between open fire and two-sided boundary fire considering the flame height and heat release rate for the two set-ups.

The dimensionless flame height for the square burner tests using propane is shown in Figure 31 when plotted against the dimensionless $\dot{Q}^*$. Figure 31(a) shows the result from each of the conducted experiments, it shows that there is a small deviation of the experiments when looking at each boundary separately. Figure 31(b) shows the average results from every experiment conducted for propane.

For propane fires conducted by one-sided boundary in small-scale there was a slight increase of 40 % in flame height, but when the small-scale propane fire was placed flush to a two-sided boundary the flame height increased further up to 100 %, giving a factor of 1.4 and 2, as seen in Table 14. For the medium scaled propane fire, the flame height increased slightly from 10 to 20 % for one-sided boundary, whereas the flame height for medium scale fires increased from 80 to 100 %, giving a factor between 1.1-1.2 for one-aided boundary and 1.8-2 for two-sided boundary.

The dimensionless flame height for the square burner test using heptane is shown in Figure 32 when plotted against the dimensionless $\dot{Q}^*$. Figure 32(a) shows the results from each of the conducted experiments and shows more deviation compared to the propane fires, when looking at each boundary separately. Figure 32(b) shows the average results from every experiment conducted for heptane.

For heptane fires conducted by one-sided boundary in small-scale there is an increase of 100 % in flame height, and when the small-scale heptane fire was placed flush to a two-sided boundary the flame height increased further up to 400 %, giving a factor 2 and 5, as seen in Table 14. For the medium scaled heptane fires, the flame height did not increase as much as the small-scale fires did. The one-sided boundary fire increased by 70 % in flame height, and when placed flush to the two-sided boundary the flame height increased further to 200 %, giving a factor 1.7 and 3, as seen in Table 14.

In previous research it has been presented a factor (called C factor in this thesis) which addresses the effect a one- and two-sided boundary will have on a fire. The C factor is found by using McCaffery's equation to find the new dimensionless energy release rate, $\dot{Q}^*_{new}$, from the experimental results shown as followed:

$$\dot{Q}^*_{new} = \left(\frac{\frac{L}{D} + 1.02}{3.7}\right)^{5/2} \qquad \textit{Eq. 13}$$

When the new dimensionless energy release rate is calculated the C factor is calculated by dividing the new dimensionless energy release rate by the dimensionless energy release rate for open, wall and corner, shown as followed:

$$C = \frac{\dot{Q}^*_{new}}{\dot{Q}^*_{boundary}} \qquad \textit{Eq. 14}$$

Table 14 C factors for the conducted experiment

	Propane Small C [-]	Propane medium C [-]	Heptane small C [-]	Heptane medium C [-]
Open	1	1	1	1
Wall	1.4	1.1-1.2	2	1.7
Corner	2	1.8-2	5	3

The dimensionless flame height for a fire with one- and two-sided boundary can then be estimated using the following equation to determine the flame height for the two configurations:

$$\frac{L}{D} = 3.7(C \cdot \dot{Q}^*)^{2/5} - 1.02 \qquad \textit{Eq. 15}$$

Eq. 15 is a variation of the simple equations suggested by Heskestad [1, 2] as presented in chapter 2.5, Eq. 12.

5 Discussion

This chapter will discuss the result from chapter 4 where the conducted experiments for open fire, one- and two-sided boundary surfaces were presented.

Experiments have been conducted to study the effect on one- and two-sided boundary surfaces to see if the boundaries have an impact on the mean flame height of pool fires using propane and heptane as fuel. The area of the fires was also considered. It was assumed there would be an impact of the flame height when placed flushed with a one-sided boundary, and even higher impact when placed flushed with a two-sided boundary.

5.1 Flame height vs. boundary

In Figure 31 the results from the propane fires are presented. As mentioned, the deviation between the conducted experiments is relatively small for both small- and medium scale propane fires. Each datapoint in Figure 31(a) represents a series of 99 photos, where the amount of propane is regulated for each experiment. The dimensionless flame height, L/D, using propane varies between 3 and 4 for small-scale and 1 and 2 for medium scale, while the dimensionless energy release rate, $\dot{Q}^*$, varies between 1.35 for small-scale and for medium scale it is set to 0.23 and 0.34. The dimensionless flame height for open propane fires (see Figure 31(b)) follows the McCaffery's equation, for both small- and medium scale. Further, it can be seen that for one-sided boundary with medium fire the dimensionless flame height as a function of dimensionless energy release rate also follows the McCaffery's equation, but one-sided boundary for small-scale do not. Two-sided boundary for both small- and medium scale do not follow McCaffery's equation and is slightly higher.

In Figure 32 the results from heptane fires are presented. For the heptane fires the deviation between the conducted experiments is more prominent for small- and medium scale heptane fires, than for propane fires. Each datapoint in Figure 32(a) represent a series of 99 photos where the same amount of heptane is poured for each of the experiments. For the experiments conducted using heptane it is seen in Figure 32(a) the results were more scattered.

The dimensionless flame height as a function of dimensionless energy release rate for heptane fires (see figure Figure 32(b)) shows that the open fire follows the McCaffery's equation, for small- and medium scale. Figure 31(b) and Figure 32(b) show the average result for flame height from the experiments conducted in small- and medium-scale, where the dimensionless flame height, L/D, ranges between 1 and

4.4 for propane fires and 2.5 and 4.7 for heptane fires. Since the HRR for the experiments conducted with propane is fixed and the experiments conducted with heptane is not, it can be assumed the height difference from propane to heptane is caused by outer factors. Heptane is poured in the pan before ignition and burns till the fuel in the pan is burned out. When placing heptane fires flush to a wall and corner the air entrainment area decreases causing the flame to “seek” more oxygen resulting the flame to stretch upwards. The behavior of the propane fires has a similar effect but does not stretch to the same extent. The assumed reason for the heptane fires to stretch to a greater length can be caused by the outer factors such as increased effect of radiation, contributing on the flame and the process the liquid heptane undergoes from liquid to gaseous form. Heptane is in liquid form and liquid does not burn before it is evaporated [27]. Because the heptane fires are affected by outer factors, the HRR increases depending on the different boundaries.

In this study the flame height was determined where the flame was obviously eminent (where the flame started shedding), because of the behavior of the flames for the different configurations. In previous research it has been stated that the flame height was defined as the limit of the existence of flame tips by visual observation [3]. Estimating the flame height is individual and the definition of flame tip can be interpreted different, so the interpretation of the flame height in this study does not necessarily corelate with previous study.

For both propane and heptane fires show clearly that for both small- and medium scale the result from open fire follows McCaffery’s equation, Eq. 3, but when the fire was placed flush to a wall the results deviated between the fuel type. Propane fires had a small to no effect when it was placed flush to a one-sided boundary for both small – and medium scale, this was confirmed by Tokunaga [3] that used a square burner with propane as a fuel. When placing the propane fire flush to a two-sided boundary the effect on the fire increased, for small-scale the increase was more notable than for medium scale.

When considering Zukoski’s approach to the reflection principle [23] the C factor is significantly lower than the factors suggested by Zukoski, for small- and medium scale using propane. But when comparing the C factor for small – and medium scale using heptane and the suggested C factor by Zukoski, the C factor was roughly the same, as seen in Table 14. Zukoski suggested a C factor 2 for wall and 4 for corner.

5.2 Mass loss rate vs. boundary

The mass loss rate for propane fires were regulated, so when conducting the experiments for the different configurations the mass loss rate for small-scale was 0.4 g/s, and 1.65 and 2.47 g/s for medium scale. So, for all configurations the mass loss rate was the same for each of the predetermined amount of propane. For the heptane fires the mass loss rate varied form each experiment and was calculated by dividing the amount of fuel poured with the time it took for heptane to burn out. When the pan was placed flush with the one-sided boundary in small-scale the mass loss rate increased only by 3 % and when placed to the two-sided boundary it had an 20 % increase. For the heptane fires conducted in medium scale the increase from open fire to one-sided boundary was approximately 9 %, but when placed flush to the two-sided boundary it increased by 46 %.

When looking at the results from the experiments using propane, small- and medium-scale configurations give a smaller C factor and does not follow the 2 and 4 factor suggested by Zukoski, as seen in Table 14. When looking at the results for the experiments using heptane, small- and medium-scale configurations do follow the 2 and 4 factor theory, as seen in Table 14. It can then be assumed that the environment had a greater impact on the heptane fires than propane fires, increasing the mass loss rate of heptane due to increased radiation from walls and flame when placed next to a wall and corner. The reasoning behind this assumption is that heptane fires are not regulated as opposed to propane fires, which were regulated and had a constant flow of propane entering the pan and was not affected by external factors.

By looking at the results from the propane and heptane fires, there is a clear difference between the C factor for the two fuels. This can be explained by the increase in mass loss rate for heptane fires when placed next to one- and two-sided boundaries. As seen in Table 9 the mass loss rate has a small increase from open fire to fire next to a one-sided boundary, but have a significant increase from open fire to a fire next to a two-sided boundary. $\dot{m}_o$ is the average mass loss rate for the open experiments for both small- and medium scale and $\dot{m}_c$ is the average mass loss rate for the two-sided boundary experiments for both small- and medium scale. So, when dividing the mass loss rate for corner heptane fires, $\dot{m}_c$, with mass loss rate for open heptane fires, $\dot{m}_o$, it results in a factor close to two. This can explain the different increase in the C factor presented in Table 14 where the C factor for heptane fires is significantly higher than for propane fires. It is assumed that the C factor will change for different fuels where mass loss rate will increase when placed next to a boundary. Since the propane flow was fixed the mass loss rate was equal for all boundaries resulting in a lower C factor than the fires containing heptane, respectfully. So, by adding an additional factor, denoted C_F, when calculating the mean flame height for heptane fires the result will be more accurate according to the results presented in this thesis.

The following equation is a suggestion to determine the dimensionless flame height for a specific fuel where the mass loss rate increases when placed next to a boundary:

$$\frac{L}{D} = 3.7 \cdot \left[(C_F + C) \cdot \dot{Q}^*\right]^{2/5} - 1.02 \qquad \text{Eq. 16}$$

Where C_F is the additional C factor for the fuel used.

5.3 Circular vs. square pans

Zukoski presented two factors, the factor 2 for fires next to a wall and the factor 4 for fires in a corner [23] which could be used in Eq. 15. The findings in this thesis show that the factors presented by Zukoski depends on the fuel type, meaning the factors correlate well with the heptane fuel, while the factors for propane fuel are less than the factors presented by Zukoski. There could be several reasons for the result to not correlate with the theory presented in previous research, one of the reasons can be the shape of the pan.

It is stated that Eq. 15 can be used for burners with different shapes [11]. When the previous experiments were conducted by Zukoski it is assumed the pan used was circular [23], but Hasemi and Tokunaga conducted experiments using a square burner when investigating the behavior of the diffusion flame when placed flush to a wall and corner [3]. When looking at the presented results and conclusion it was stated the fire which is placed by a one-sided boundary the air entrainment was 50 % less and 75 % less than for two-sided boundary, compared to an open fire. Tokunaga experienced a lower increase in flame height than Zukoski, so it can be assumed that because of the shape of the burner the air entrainment for the different fires could act different. This needs to be investigated further.

5.4 Gaseous vs. liquid

Propane and heptane are both a flammable liquid. It is known that the liquid itself do not burn, but the evaporated gas from the liquid does [28]. For the propane fires the gas had already gone through the stage of vaporization when entering the burning surface of the pan, which is not the case for the heptane liquid fires. There the heptane is poured in liquid form and vaporizes while the fuel is burning. This could have had an impact on the fire. While the heptane was burning the temperature increased causing the mass loss rate to increase [29].

5.5 Other factors

The experiments were conducted on two different locations and was executed over a long period of weeks. For the experiments conducted at the university, the pool fire was placed beneath the ventilation system, which needed to be turned on during the experiments, this could have had an impact on the result. For the open fire for both propane and heptane fires the ventilation system caused the flame to move in a circular movement, but when placed flush to a one- and two-sided boundary the fire seemed unaffected. For the experiments conducted at ResQ the ventilation system was located in the back of the hall, a few meters from the pool fires. The ventilation system was turned off during the experiments so it would not have an impact on the flame. The hall was vented between every experiment. Because of the difference between the small- and medium scale experiments considering the ventilation, it is not possible to exclude that the outcome of the result could be different.

Lip height or freeboard which is the distance from the rim of the pan to the fuel surface is not taken in consideration in this thesis. But the lip height could have had an impact on the mass loss rate. A recent study showed that the mass loss rate decreased when the lip height increased [30]. This would make a difference between the small- and medium scale fires because of the area of the pan. The lip height would increase more rapid for small-scale than for medium scale causing the mass loss rate to decrease in a larger degree than for medium scale.

5.6 Overall findings

Previous research [1, 3, 4, 23, 24, 25, 31] discussed in this thesis show some similarities to the result presented in this thesis. It shows that there is an increase in flame height when placing fire flushed next to one- and two-sided boundaries. As previous mentioned the flame is turbulent and will behave differently for each experiment conducted, so it will be difficult to establish an exact equation to calculate the mean flame height without doing an extent of experiments. So, when looking at the factors suggested by Zukoski and comparing his findings to other research including this thesis, it can be concluded that there will be an effect on the flame height when a fire is exposed to boundaries.

6 Conclusion

This study focused on the effect one- and two-sided boundaries will have on a square pool fire using different fuel type and different scale, when considering the mean flame height.

The overall results show that there is an effect to the fires when placed flush to a one-sided boundary, the increase in flame height was approximately between 20 and 200 % depending on the fuel used. When the fire was placed flush to a two-sided boundary the increase in flame height where between 100 and 400 % depending on the fuel used.

The experimental results for the mean flame height in this study showed a various increase in flame height when comparing the fuel used and size of the HRR. For the fires containing heptane the small-scale experiments showed an increase in mean flame height by 100 % when placed flush to a one-sided boundary and 400 % when placed flush to a two-sided boundary. For the medium scale fires containing the same fuel the increase was approximately the same as for the small-scale experiments when placed flush to a one-sided boundary and had an 70 % increase. When placed next to a two-sided boundary the increase for the medium scale, the mean flame height had an 200 % increase.

For the experiments containing propane the fires showed an overall lower increase in mean flame height comparing to the experiments containing heptane. The experimental result for propane fire showed an 40 % increase in flame height when exposed to one-sided boundary in small-scale, and 10-20 % increase in flame height in medium scale. When placed flush to a two-sided boundary the fire had an 100 % increase in small-scale and between 80-100 % increase in flame height in medium scale.
The overall result shows that the fires placed flush to a one-sided boundary show a lower increase in flame height for propane fires than first expected, while the fires containing heptane had an increase similar to the theory behind the Zukoski factors.

Both propane and heptane fire show clearly that for open and one-sided boundary the flame height follows McCaffery's equation, but when placed flush to a two-sided boundary the result deviate when dimensionless flame height as a function of dimensionless energy release rate is used. This confirms partly the results given by Zukoski [23] where a factor is needed to determine the calculated mean flame height when exposed to boundaries.

There will perhaps be needed an additional factor to the suggested equation presented in Eq. 15 which equals the higher increase in flame height for the fires containing heptane. This can be done by reducing the C factor for heptane to make the C factor equal the C factor for propane. To account for the reduction for the heptane C factor an addition factor is presented, C_F.

7 Further work

Based on the work done in this thesis, the following suggestions are made for further work:

- Investigate to see if there is an important difference between circular and square pans used when conducting experiments with boundaries when using Zukoski's factor to calculate the mean flame height.
- Conducting experiments where the amount of heptane is fed constantly during the experiments to see if the lip height has an impact on the mean flame height.
- Investigate to see how different sized pool fire will increase in flame height when exposed to one- and two-sided boundary surface.
- Investigate to see if the increase in mass loss rate for different fuels when placed next to a boundary will affect the C factor where an additional C factor will be needed to determine the dimensionless flame height for a fire placed next to a boundary for a variation of fuel.

8 References

[1] G. Heskestad, "Chapter 13. Fire Plumes, Flame Height, and Air Entrainment," in *SFPE Handbook of Fire Protection Engineering*, Springer, 2016, pp. 396-428.

[2] G. Heskestad, "Luminous Height of Turbulent Diffusion Flames," Fire Safety Journal, 1982.

[3] Y. Hasemi and T. Tokunaga, "some Experimental Aspects of Turbulent Diffusion Flames and Buoyant Plumes from Fire Sources Against a Wall and in a Corner," Gordan and Breach Science Publishers Inc., Combustion Science and Technology, 1984.

[4] K. McGrattan, M. Selepak and E. Hnetkovsky, "The Influence of Walls, Corners and Enclosures on Fire Plumes," NIST National Institute of Standards and Technology, 2018.

[5] D. Drysdale, " Chapter 1. Fire Science and Combustion," in *An Introduction to Fire Dynamics*, Wiley, 2011, pp. 1-34.

[6] D. D. Drysdale, "Chapter 18. Ignition of Liquids," in *SFPE Handbook of Fire Protection Engineering, fifth Edition*, Springer, 2016, pp. 554-603.

[7] B. Karlsson and J. G. Quintiere, "Chapter 4. Fire Plumes and Flame Heights," in *Enclosure Fire*, CRC Press, 2000, pp. 47-80.

[8] D. Drysdale, "Chapter 4. Diffusion Flames and Fire Plumes," in *An Introduction to Fire Dynamics*, Wiley, 2011, pp. 121-180.

[9] J. Casal, "Chapter 3. Fire Accidents," in *Evaluation of the Effects and Consequences of Major Accidents in Industrial Plants*, Elsevier, 2018, pp. 75-150.

[10] J. G. Quintiere, "Chapter 6. Burning Rate," in *Principles of Fire Behavior*, Delmar Publishers, 1998, pp. 101-128.

[11] B. Karlsson and J. G. Quintiere, "Chapter 3. Energy Release Rates," in *Enclosure Fire*, CRC Press, 2000, pp. 25-46.

[12] V. Babrauskas, "Chapter 26. Heat Release Rates," in *SFPE Handbook of Fire Protection Engineering, fifht edition*, Springer, 2016, pp. 799-904.

[13] D. D. Drysdale, "Chapter 5. Thermochemistry," in *SFPE Handbook of Fire Protection*, Springer, 2016, pp. 145-146.

[14] G. E. Gorbett, J. L. Pharr and S. R. Rockwell, "Chapter 2. Fire Basics," in *Fire Dynamics, second edition*, Pearson , 2016, pp. 16-33.

[15] M. Janssens, "Chapter 27. Calorimetry," in *SFPE Handbook of Fire Protection Engineering, fifth Edition*, Springer, 2016, pp. 905-951.

[16] A. S. Rangwala, "Chapter 11. Diffusion Flames," in *SFPE Handbook of Fire Protection Engineering, fifth edition*, Springer, 2016, pp. 350-372.

[17] Blinov and Khudiakov, "Diffusion Burning of Liquids," US Army Translation, 1961.

[18] J. G. Quintiere, "Chapter 10. Fire Plumes," in *Fundamentals of Fire Phenomena*, Wiley, 2006, pp. 297-338.

[19] B. C. Hagen, "Chapter 14. Røykproduksjon," in *Grunnleggende brannteknikk*, 2018.

[20] G. E. Gorbett, J. L. Pharr and S. R. Rockwell, "Chapter 7. Heat Release Rate," in *Fire Dynamics, second edition*, Pearson, 2016, pp. 117-150.

[21] K. McGrattan and S. Miles, "Chapter 32. Modeling Fires using Computational Fluid Dynamics (CFD)," in *SFPE Handbook of Fire Protection Engineering*, Springer, 2016, pp. 1034-1065.

[22] T. B. Maynard and J. W. Butta, "A physical Model for Flame Height Intermittency," pp. 135-161, 24 September 2017.

[23] E. E. Zukoski, "Chapter 3. Properties of Fire Plumes," in *Combustion Fundamentals of Fire*, Geoffrey Cox, Academic Press, 1995, pp. 101-219.

[24] F. W. Mowrer and R. B. Williamson, "Estimating Room Temperatures from Fires along Walls and in Corners," *Fire Technology*, pp. 133-145, May 1987.

[25] W. Takahashi, H. Tanaka, O. Sugawa and M. Ohtake, "Flame and Plume Behavior in and near a Corner of Walls," Fire Safety Science, 1997.

[26] D. J. Rasbash, Z. W. Rogowski and G. W. Stark, "Properties of Fires of Liquids," in *Fuel A Quarterly Journal of Fuel and Combustion Science*, Butterworths Scientific Publications, 1956, pp. 94-107.

[27] OSHA's Directorate of Training and Education, "www.osha.gov," 2016. [Online]. Available: https://www.osha.gov/sites/default/files/training-library_TrngandMatlsLib_FlammableLiquids.pdf. [Accessed 2021].

[28] U. S. D. o. Labor, "Flammable Liquids," [Online]. Available: https://www.osha.gov/sites/default/files/training-library_TrngandMatlsLib_FlammableLiquids.pdf. [Accessed 2021].

[29] B. Hagen, "Chapter 11. Brannkjemi," in *Grunnleggende Brannteknikk*, 2016, pp. 149-174.

[30] E. Kolstad, V. Flette and B. C. Hagen, "Lip Height Effect in Quadrangular steel contaioners".

[31] M. Poreh and G. Garrad, "A Study of Wall and Corner Fire Plumes," Fire Safety Journal, 2000.

9 Appendix

9.1 Experiment overview

Shows an overview of all the experiments conducted, the log name, the amount of fuel used and the temperature inside and outside the fire lab.

SMALL SCALE HEPTANE					
Experiment	Pan number	Temperature log name	Amount of liquid[g]	Temperature inside [˚C]	Temperature outside [˚C]
OHS-1	P-4	OHS-Log 1	100.00	14.2	4.0
OHS-2	P-4	OHS-Log 2	100.00	15.0	4.0
OHS-3	P-4	OHS-Log 3	100.40	15.0	5.0
WHS-1	P-4	WHS-Log 4	100.18	15.4	3.0
WHS-2	P-4	WHS-Log 5	100.10	15.4	3.0
WHS-3	P-4	WHS-Log 6	100.20	15.4	3.0
CHS-1	P-4	CHS-Log 7	100.00	14.0	1.0
CHS-2	P-4	CHS-Log 8	100.00	14.1	1.0
CHS-3	P-4	CHS-Log 9	100.20	14.1	1.0

BIG SCALE HEPTANE					
Experiment	Pan number	Temperature log name	Amount of liquid[g]	Temperature inside [˚C]	Temperature outside [˚C]
OHB-1	P-3	OHB-Log 1	1350.90	12.1	11.0
OHB-2	P-3	OHB-Log 2	1350.40	13.7	11.0
OHB-3	P-3	OHB-Log 3	1350.50	14.0	11.0
OHB-4	P-3	OHB-Log 4	1350.90	14.0	11.0
OHB-5	P-3	OHB-Log 5	1350.30	14.7	11.0
WHB-1	P-3	WHB-Log 6	1350.92	14.5	11.0
WHB-2	P-3	WHB-Log 7	1350.56	9.5	9.0
WHB-3	P-3	WHB-Log 8	1350.25	10.8	9.0
WHB-4	P-3	WHB-Log 9	1350.30	11.8	9.0
WHB-5	P-3	WHB-Log 10	1350.15	12.5	9.0
CHB-1	P-3	CHB-Log 11	1350.10	12.0	10.0
CHB-2	P-3	CHB-Log 12	1350.09	13.7	10.0
CHB-3	P-3	CHB-Log 13	1350.40	14.1	10.0
CHB-4	P-3	CHB-Log 14	1350.43	14.1	10.0
CHB-5	P-3	CHB-Log 15	1350.32	13.8	10.0

SMALL SCALE PROPANE					
Experiment	Pan number	Temperature log name	Gas amount [g/s]	Temperature inside [˚C]	Temperature outside [˚C]
OPS-1	P-1	OPS-Log 1	0.4	15.0	4.0
OPS-2	P-1	OPS-Log 2	0.4	15.0	4.0
OPS-3	P-1	OPS-Log 3	0.4	15.0	4.0
WPS-1	P-1	WPS-Log 4	0.4	15.3	3.0
WPS-2	P-1	WPS-Log 5	0.4	15.3	3.0
WPS-3	P-1	WPS-Log 6	0.4	16.0	3.0
CPS-1	P-1	CPS-Log 7	0.4	14.0	4.0
CPS-2	P-1	CPS-Log 8	0.4	14.0	4.0
CPS-3	P-1	CPS-Log 9	0.4	14.0	4.0

BIG SCALE PROPANE					
Experiment	Pan number	Temperature log name	Gas amount [g/s]	Temperature inside [˚C]	Temperature outside [˚C]
OPB-4-1	P-2	OPB-Log 1	1.65	10.5	10.0
OPB-4-2	P-2	OPB-Log 2	1.65	11.0	10.0
OPB-4-3	P-2	OPB-Log 3	1.65	11.5	10.0
OPB-4-4	P-2	OPB-Log 4	1.65	11.3	10.0
OPB-4-5	P-2	OPB-Log 5	1.65	11.5	10.0
OPB-6-1	P-2	OPB-Log 6	2.47	11.3	10.0
OPB-6-2	P-2	OPB-Log 7	2.47	11.3	10.0
OPB-6-3	P-2	OPB-Log 8	2.47	11.8	10.0
OPB-6-4	P-2	OPB-Log 9	2.47	11.8	10.0
OPB-6-5	P-2	OPB-Log 10	2.47	12.0	10.0
WPB-4-1	P-2	WPB-Log 11	1.65	10.5	7.0
WPB-4-2	P-2	WPB-Log 12	1.65	10.5	7.0
WPB-4-3	P-2	WPB-Log 13	1.65	10.8	7.0
WPB-4-4	P-2	WPB-Log 14	1.65	11.0	7.0
WPB-4-5	P-2	WPB-Log 15	1.65	11.1	7.0
WPB-6-1	P-2	WPB-Log 16	2.47	15.1	14.0
WPB-6-2	P-2	WPB-Log 17	2.47	19.5	14.0
WPB-6-3	P-2	WPB-Log 18	2.47	11.5	7.0
WPB-6-4	P-2	WPB-Log 19	2.47	11.3	7.0
WPB-6-5	P-2	WPB-Log 20	2.47	11.6	7.0
CPB-4-1	P-2	CPB-Log 21	1.65	14.1	11.0
CPB-4-2	P-2	CPB-Log 22	1.65	14.1	11.0
CPB-4-3	P-2	CPB-Log 23	1.65	14.2	11.0
CPB-4-4	P-2	CPB-Log 24	1.65	14.5	11.0
CPB-4-5	P-2	CPB-Log 25	1.65	14.5	11.0
CPB-6-1	P-2	CPB-Log 26	2.47	14.0	13.0
CPB-6-2	P-2	CPB-Log 27	2.47	14.4	13.0
CPB-6-3	P-2	CPB-Log 28	2.47	14.5	14.0
CPB-6-4	P-2	CPB-Log 20	2.47	14.7	14.0
CPB-6-5	P-2	CPB-Log 30	2.47	14.8	14.0