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Boil-off gas handling for LNG-carriers with a low-swirl burner

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Summary:

Wärtsilä is looking into a new technology for boil-off gas handling. The technology chosen for further research is a low-swirl burner. This burner has shown promising NO_x emission results which is a problem inside the shipping industry. The system is a combined high/low-swirl burner that could handle both premixed- and none-premixed mixture.

The objective for the project is to find a correlation between swirl-number and flame shape. This has been done using algebraic equations and images of the flame. Burner design was unchangeable during this thesis thus the selection of swirl-numbers was limited.

Experiment was conducted at Wärtsilä Moss in large scale. A high-speed camera analyzation was intended but due to uncontrollable factors a thermal camera had to be used.

This thesis has discovered the optimal swirl-numbers for the given design to achieve the characteristic low-swirl flame shape. The correlation between swirl-number and flame shape is discovered for the combined high/low-swirl burner.

Preface

This Thesis is the closing project of a 2-year master program in Process Technology and was written during spring 2018. The project was conducted at the Faculty of Technology, Natural- and Maritime Science. The thesis was written at the University of South-Eastern Norway. It is assumed that the person reading this thesis has some prior knowledge to terminology inside fluid dynamics and/or combustion.

I would like to thank my supervisor PhD Joachim Lundberg for good guidance through the project and his ability to always be available when needed. A big thank you my external partner Odd Ivar Lindløv for informative answers to my questions and inputs. Will also thank Knut Vågsæther for good answers when asked.

I wish to thank Sondre Slathia (my brother-in-law) that have helped me with data issues and guidance.

Lastly, I wish to thank my parents for supporting and encouraging me through my studies.

Porsgrunn, 14.05.2018

Stian Melkevik

Contents

1 Introduction

Wärtsilä Moss is doing research and experiements of a new system for boil-off gas handling for Liquefied Natural Gas-carriers (LNG-carriers). This introduction chapter contains background and motivation for this thesis. There is a heading where the objectives for this report is presented. The structure of this report is included to give an overview of the contents in the different chapters.

1.1 Background and Motivation

LNG-carriers are large vessels used in transportation of liquefied natural gas (LNG). The vessels are designed with several tanks that contains LNG ready for transportation. Due to large temperature differences between the LNG (-163ºC) and surroundings a small amount of the cargo will evaporate despite good tank insulation. This evaporation creates a small layer of evaporated LNG in the top of the tank which is known as boil-off gas (BOG). This phenomenon is unavoidable and the BOG has to be removed to keep correct cargo pressure [1]. Wärtsilä which is provider of this thesis offers technology to handle the BOG today but want to develop a new technology that is more reliable and less expensive.

One of the systems Wärtsilä offers today is reliquefaction of BOG, this system demands much space due to redundancy. Since a vessel has limited space and redundancy in a system is expensive they consider a new technology. Wärtsilä offers a system that is similar to the system described in this thesis today but due to strict emission demands they are looking for improvements. Especially emission from the pollutants NO_x and CO is a problem. The technology needs to show promising low-emission results due to strict emission regulations.

A concept of a combined high/low-swirl burner provided by Wärtsilä is chosen as the technology for further research. The low-swirl burner is used while the vessel is in operation to burn off the BOG and the high-swirl burner is used before inspection and/or ventilation of the tanks to burn out volatile gas that is not premixed. An introduction to this system will be given in Chapter 2 of this thesis.

This thesis will contain results from the experiments and an analysis of the results. A comparison with previous work will also be shown for verifying the results accomplished.

The main focus of this thesis is to find a correlation between swirl number and flame shape. This will be presented by mathematical models and images from experiments where it will be shown what type of flame shape that is obtained. Mathematical models are used to describe the phenomenon of the combustion for both low- and high-swirl. In this thesis the variation of swirl number will be a central part of evaluate the flame shape.

1.2 Objectives

This Master´s thesis will contain the following objectives:

- A survey on what type of technology that is provided today and why new technology is wanted.
- A literature study on existing high/low-swirl burning technology and operation principles associated with these type of burners.

- An overview of mathematical models used to describe different mechanisms and design parameters associated with the burner.
- A mathematical model used to design this type of technology and investigate benefits associated to the combined high/low-swirl burner technology.
- Investigate which parameters that is important for the burner design and combustion mechanisms, thus can give an indication on the correlation between flame shape and swirl number.
- An overview of emission associated with the high/low-swirl burners.

1.3 Structure of the Thesis

This heading describes each chapter in the thesis and a following description.

- Chapter 2:

This chapter presents basic theory about the system provided today and intended system. Both reliquefaction and high/low-swirl technology will be presented with figures and basic introduction of functionality.

- Chapter 3:

In this chapter a more detailed description of operating principles will be presented. Difference between non-premixed and premixed and a detailed description of low-and high-swirl. In this chapter the intended system of combined high/low-swirl is described and crucial design parameters are discussed.

- Chapter 4:

This chapter contains the mathematical models used for design and analysis of the combined high/low-swirl burner.

- Chapter 5:

Due to strict emission demands from authorities inside the shipping industry this chapter contains some of the problem associated with the emission from the shipping industry. This thesis has focused on the emission of NO_x and CO.

- Chapter 6:

In this chapter the results from the experiments is presented such as images and calculations. This is compared to previous work to verify if the results are comparable to previous experiments.

- Chapter 7:

Discussion around the combined high/low-swirl burner as a technology for handling boil-off gas and the emission results is presented. This chapter also contains a discussion around the results found in this thesis.

- Chapter 8:

Conclusion and recommendation for further work is presented.

2 Theoretical Background

In this chapter existing and the new boil-off gas systems will be presented and described without a very technical description. In these type of systems three scenarios could occur that is important in boil-off gas handling. The systems presented are different system which means they do not need to cover all three scenarios since the basic of the systems is different. The three scenarios are as follows:

- Boil-off gas handling, a system to get control of the boil-off gas.
- Inert gas production to avoid hazard situations under cargo handling.
- Before ventilation of the tanks the inert gas has to be removed, the system needs to handle this type of problem.

Inert gas is the main safety system onboard a vessel due to insufficient combustion of hydrocarbons. This system is designed to avoid explosions and contain tank pressure in situations like off-loading or before entering the tank for inspection [2].

2.1 Reliquefaction System

The reliquefaction system offered by Wärtsilä today is a technology where the boil-off gas is reliquefied and transported back to the LNG tanks. BOG goes through a compressor to increase pressure before it enters a heat exchanger. The heat exchanger cools it down before returning to tanks is a very simplified description of the system. This system reuses the BOG which is a big advantage because it reduces emission by recycling the BOG back into the holding tanks [1]. Due to recirculation of BOG and no need of a combustion unit this system has a minimal environmental footprint from NO_x and CO emission. Figure 2.1 gives an indication on how large the system is, and that the system is designed with redundancy. Redundancy is required because the system is in need of a backup system in case of a breakdown [3].

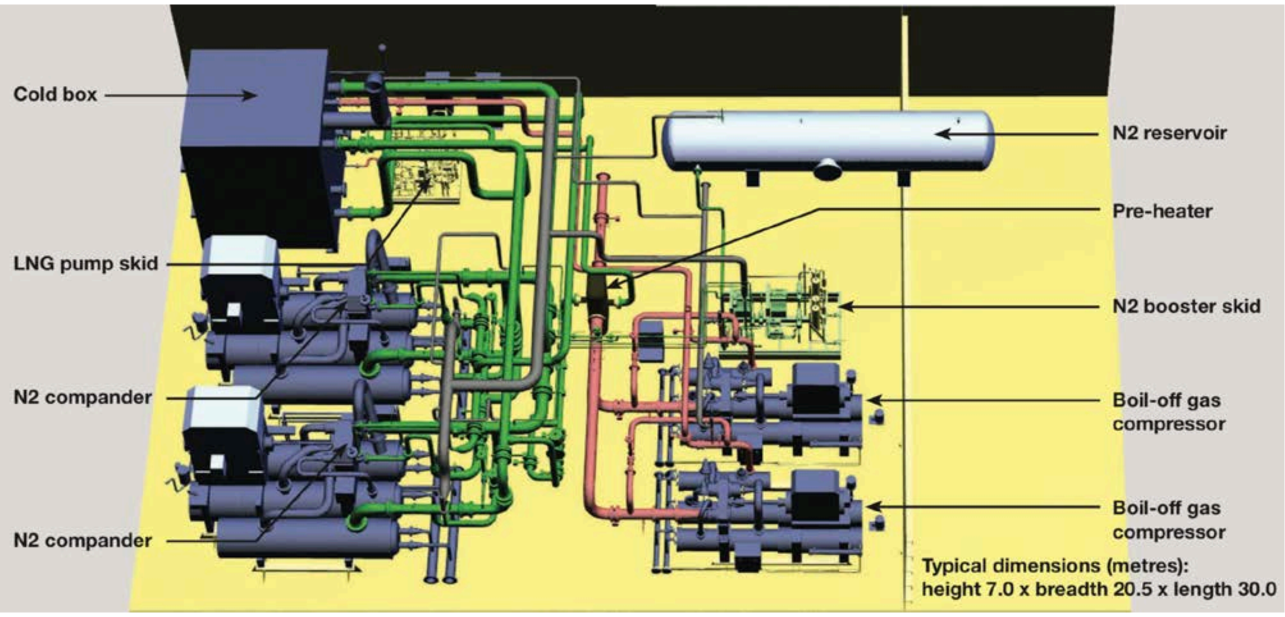

Figure 2.1: Reliquefaction system with dimensions and associated equipment [3].

This system will according to Wärtsilä system description increase the cargo delivered due to reliquefaction of boil-off gas. As much as total LNG loaded can be delivered to the customer. The system is in no need of extra personal for operation or maintenance and has an automatic capacity control which makes it easy to adjust the quantity of BOG [3].

This system provides a good solution to BOG handling which is one of the scenarios the system must handle. It uses nitrogen as inert gas component. This is stored in on-board tanks since the system itself is incapable of producing. This system handles the BOG problem connected to LNG-carriers in a sufficient way.

2.2 Burner/scrubber system

A system that is similar to the combined high/low-swirl technology is offered today and is an inert gas generator system (IGG). This technology uses a combined unit that contains both burner and scrubber. The system uses a burner, this would lead to emission of both NO_x and CO [2]. The scrubber is a cleaning method which uses seawater to cool and clean the gas before entering the environment [1]. As for the other system this also provides high safety due to remain cargo pressure in the tanks. In this system the BOG is burned in a controlled way to avoid hazardous situations and uses the scrubber to clean the gas. The system is also possible to implement in already existing systems and offers an option to save some space due to compactness. Inert gas generator is optimized to only create the inert gas needed to maintain tank pressure.

Wärtsilä states that this is the most space saving system design known, which is an important parameter in a space limited area. This system offers a solution to all of the scenarios described in the introduction for Chapter 2. In Figure 2.2 the design and connection with other equipment is illustrated [2].

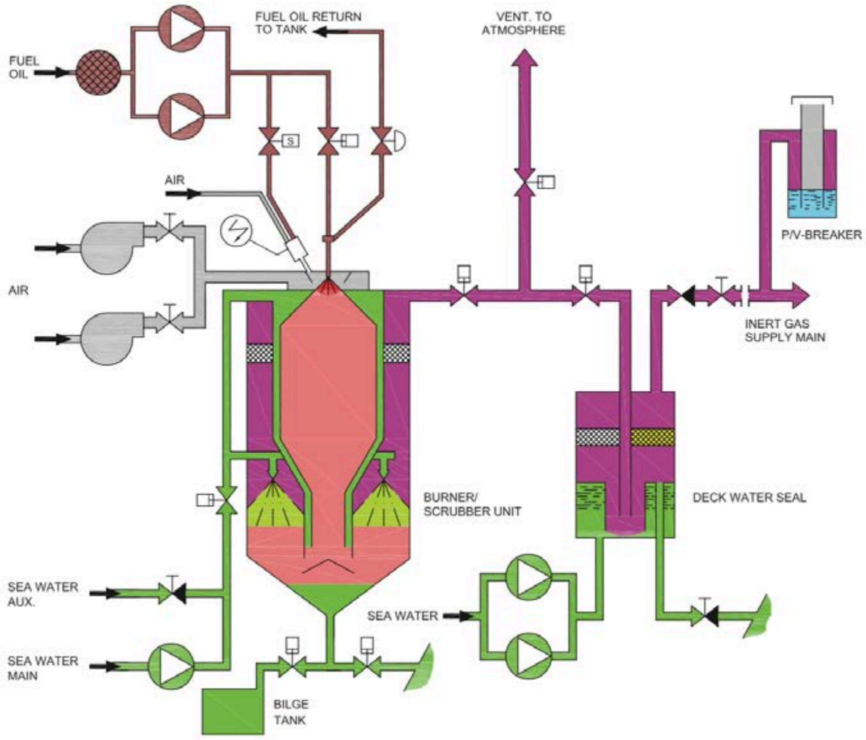

Figure 2.2: Schematic of the Burner/scrubber system [2].

2.3 Combined high/low-swirl Technology

In this chapter a brief introduction to the intended system will be given while the mechanism connected with the system will be presented in Chapter 3. Explanation of why this system is something Wärtsilä want to investigate further and why it is such a promising technology.

The system is intended to burn out the BOG with an emission friendly technology called low-swirl burner. This type of burner has shown promising low NO_x and CO emission. [4]. When the LNG-carriers is in need of an inspection or for some reason have to ventilate the tank the low-swirl burner is connected with an inert-gas-generator (IGG) that is filling the tank with inert-gas. As inert-gas in this system CO_2 is chosen. After the LNG is offloaded, the tank is filled with inert-gas (CO_2). The tanks are filled with inert-gas and is mixed with other gases in the tanks. This has to be combusted in a sufficient way before entering the environment. For this purpose, a high-swirl burner with a diesel spray mounted at the tip of the burner to get a stable flame. The diesel spray has to be used as the level of CO_2 increasing and the stoichiometry is out of range which demands an external ignition/combustion source due to an unburnable mixture.

As illustrated in Figure 2.3 the low-swirl burner is intended to burn out the BOG and create inert gas that is injected into the tanks during offload of LNG or ventilating/inspection of tanks. The high-swirl burner is intendent to combust the mixture inside the tank before ventilating/inspection. A diesel spray is used to create a combustible mixture.

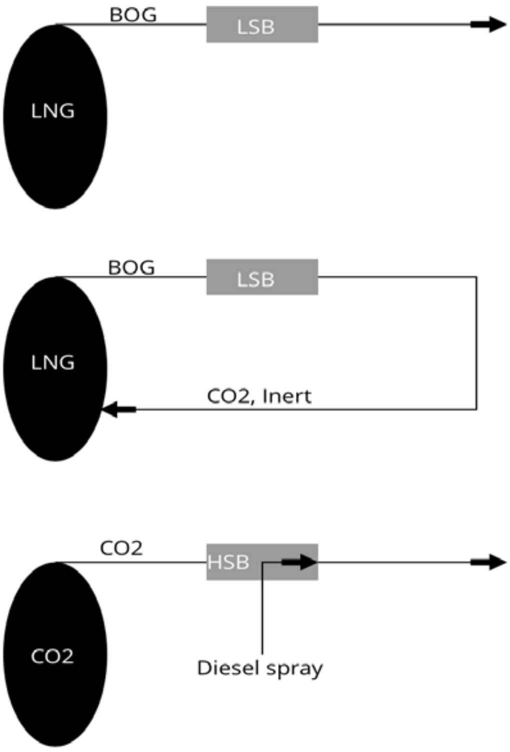

Figure 2.3: Illustration of different scenarios

Figure 2.4 is a photograph of the different part included in the system, premix unit, burner and combustion chamber are all located in the picture [5]. In the premix unit the wanted composition is made prior to the burning. This composition could be lean or rich and is in this case a lean composition which indicates that the equivalence ratio is below 1 [6]. The well-mixed composition is then ready to enter the burner.

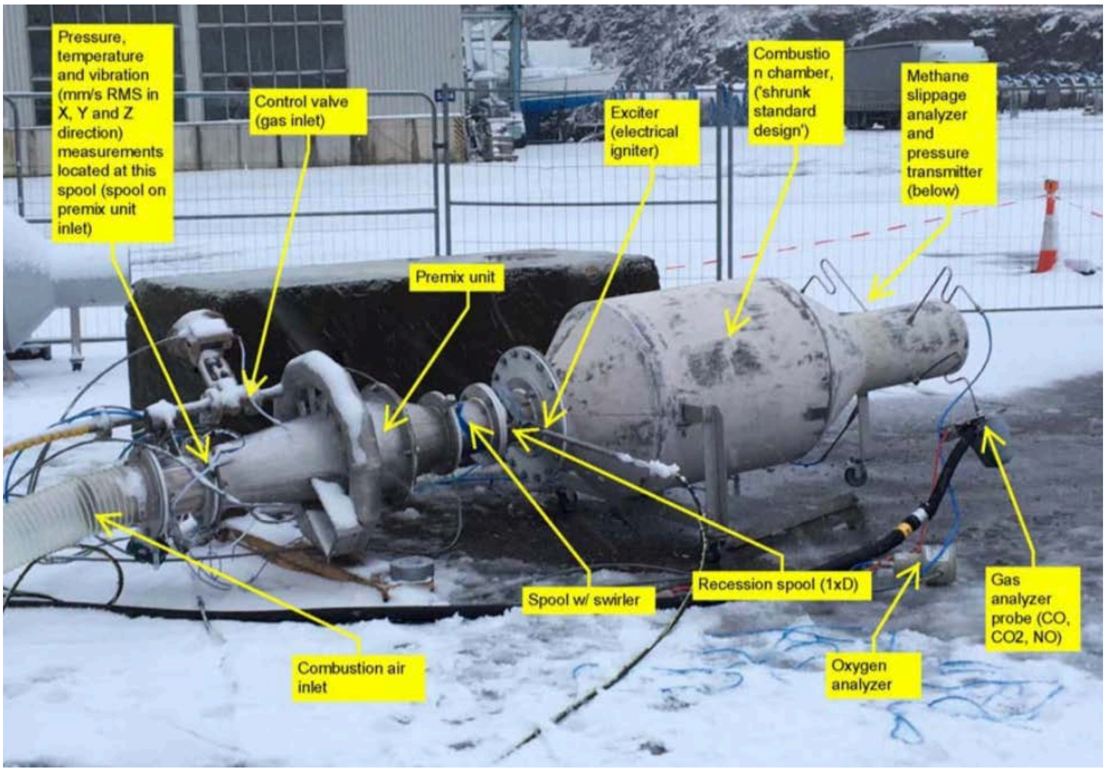

Figure 2.4: Burner design [5].

In Figure 2.5 an image of the burner is shown where the center channel (holes) is for low-swirl operation. The number of holes is changeable due to different blockage area. In this thesis the number of holes has been 100, 110 and 120. This gives a different blockage ratio which changes the swirl number due to variation in blockage area. Wärtsilä has combined a low-swirl and high-swirl burner which applies that it is possible to close the center channel in operation that changes the burner from low-swirl to high-swirl. In the outer region of the burner (annulus) is where the swirling vanes are placed. This will give the flow through the annulus a swirling motion. A nut is placed in the center of the burner this is going to be replaced with a diesel nozzle in the real burner but is not done in experiment conducted in this thesis. The composition of the gas mixture is then entering the burner and is burned in the combustion chamber [5].

Figure 2.5: Burner design [5].

One of the main advantages with this system is the size, this system is similar to the burner/scrubber system [5]. The system is also adjustable and easy to implement in already existing equipment. Low-swirl burner offers a reliable system that has a low cost, good efficiency and hopefully can offers low emission results (in large scale) as it does in small scale test rigs [4]. Through experiments and mathematical models presented in Chapter 4 it will hopefully give an indication that this technology is something to investigate further.

The mechanism that makes it unique is to combine high- and low-swirl in one device. The low-swirl burner operates as a premixed flame and is dependent of a well-mixed composition to burn as it is indented to do. The high-swirl burner operates a different way, not dependent of a premixed flame. The inert gas is CO_2 as mentioned and shown in Figure 2.3. This gas is injected into the tanks before ventilation and/or inspection of the tanks. Inside the tank where it used to be LNG it now contains a mix of different substances. These substances are in combination with a diesel spray combusted with a high-swirl burner to avoid emission straight out in the atmosphere. Therefore, the high-swirl burner is intendent to burn out the rests which is inside the tank. CO_2 is not a flammable gas, but the tank could contain remains of other substances that will be combusted in combination with a diesel spray. Since the composition is not possible to premix a low-swirl burner would not be suited for the task. By combine these two technologies or configurations it gives a burner that handles the boil-off gas in an environment friendly way (low-swirl) and a method to avoid emission of remains in the tanks to the atmosphere (high-swirl). This makes the system unique due to the size of the burner and hopefully a system that is less expensive than systems offered today.

Wärtsilä is pending patent on the combined high/low-swirl system while this thesis is written.

3 Operating principles

In this chapter characteristics for low- and high-swirl is presented as well as the associated mechanisms that generates different flame shape for the two burners. These two techniques require a different approach in the burner which will be enlighten in this chapter. An explanation of why the swirl-burner is an environment friendly method to handle boil-off gas is another parameter that will be mentioned but described in detail in Chapter 5.

3.1 High-Swirl

For explanation of the different mechanisms and how the high-swirl burner operates, Figure 3.1 is presented.

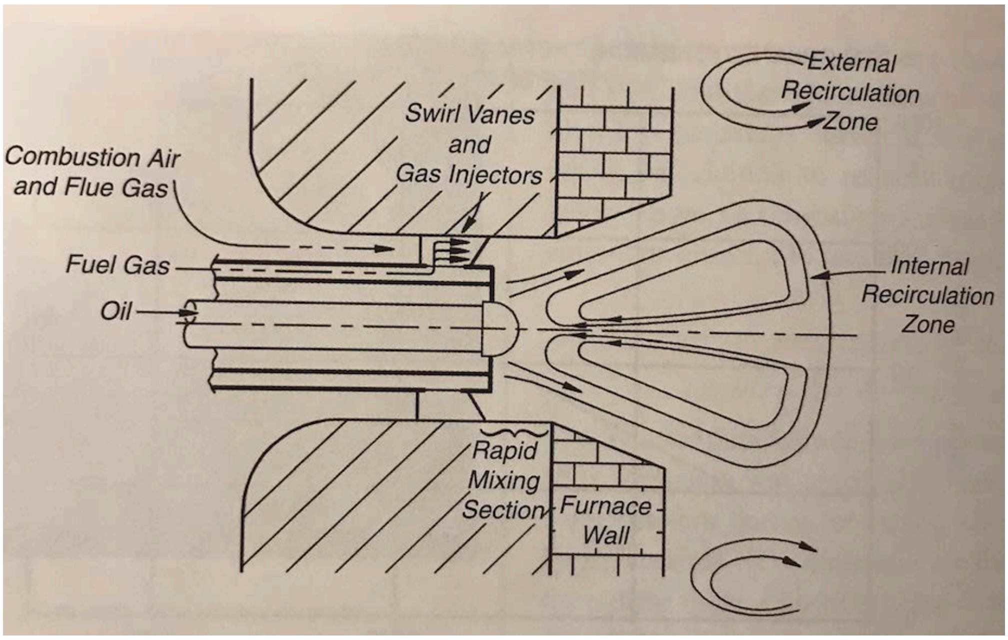

Figure 3.1: High-swirl burner design/mechanisms [7].

The design is crucial in a high-swirl burner. High-swirl burner use guiding vanes which is bend with an angle that gives the combustion air a swirling motion. This becomes the recirculation zone which creates a stable flame and helps igniting the fuel. In the recirculation zone mixing of air and fuel also occur. In a high-swirl burner the flame will be attached to the burner and look like a jet flame (cylindrical shape) [8].

At the inlet section the fuel is entering the burner and the oil inlet in the middle is where Wärtsilä intend to have the diesel nozzle. This gives a flame stabilized around the exit section of the burner. The swirl vanes are designed to create motion in the outlet flow which will generate the internal recirculation zone. This due to recirculate hot combustion gas that generates lower flame temperature. Lower flame temperature gives lower NO_x emission values as the NO_x is temperature dependent which will be described in detail in Chapter 5.

In the intended system CO_2, air, diesel and a mixture of other gases would be the composition as described earlier. In the experiment this has not been possible to try which makes an analysis of the high-swirl configuration difficult. The high-swirl burner has been used with a premixed methane-air flow, the same as the low-swirl configuration. The only difference is the center part which is closed. A composition of CO_2, air and diesel would probably not be a lean mixture and certainly not a methane-air composition. This makes the analysis with the mathematical models presented in Chapter 4 invalid for calculating the laminar flame speed and equivalence ratio. Therefore, the important thing to sort out before further research is if it is possible to change between a high-swirl to low-swirl configuration.

3.2 Low-Swirl

As for the previous chapter about high-swirl an illustration given in Figure 3.2 is shown to describe the operation principles.

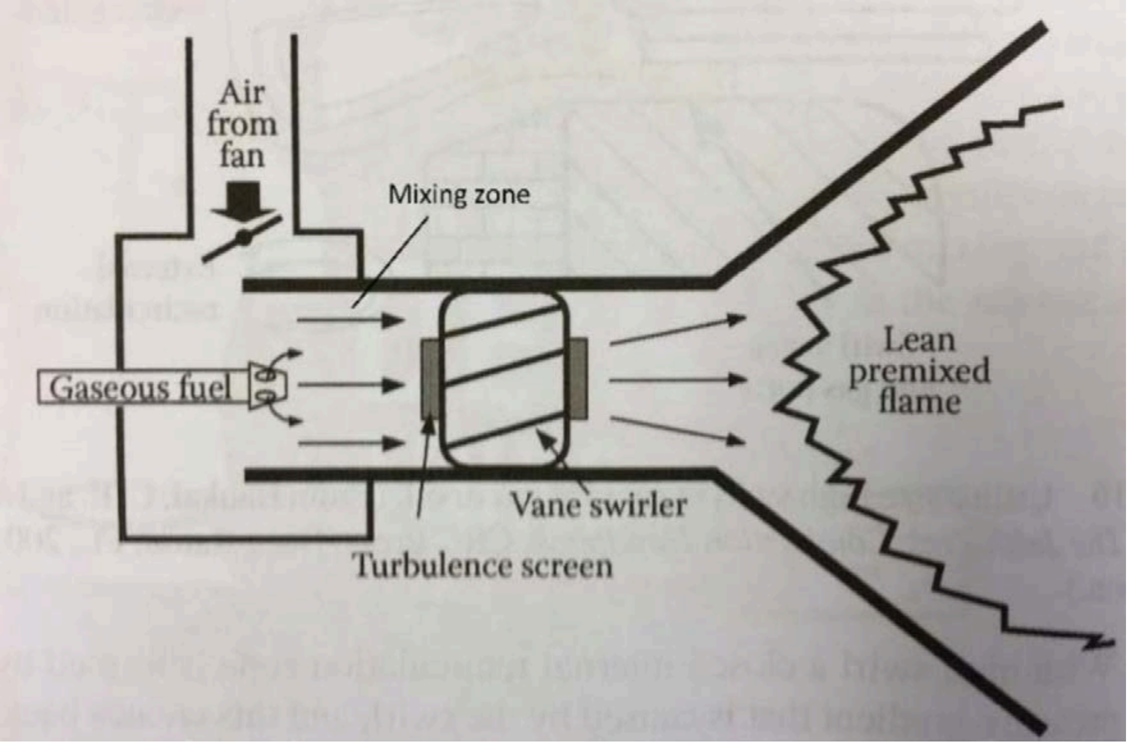

Figure 3.2: Low-swirl burner design/mechanisms [9].

As tried to illustrate the low-swirl flame is not attached to the burner but settles outside the burner exit. The low-swirl burner is dependent on a premixed composition to burn a lean flame that is stable. The flame will stabilize where turbulent burning velocity equals local flow velocity, this will be described further in the Chapter 4 about the mathematical models. One major difference between low- and high-swirl configuration is the recirculation zone. As shown in the Figure 3.2 there is no recirculation zone. The reason why the low-swirl burner is designed to not have a recirculation zone is due to lowering turbulence intensity [4]. As mentioned the low-swirl burner does not have a strong recirculation zone which together with the longer residence time and lower combustion temperature is why it reduces NO_x emission [10]. Emission connected to the low-swirl burner is explained in Chapter 5.

In a low-swirl burner compared to a high-swirl burner the center plate is open which allows the reactants to pass by. This gives a swirled flow in the annulus section and a unswirled flow in the center channel. The result of this is a split flow where the unswirled flow produces a turbulence. The swirling motions and the center flow will expand and create the flame [4].

4 Mathematical models

This chapter contains mathematical models that is used for designing and operational principles connected to the burner. The analyzation of the experiments uses the mathematical models described in this chapter as a basis.

First of all, it is important to state content of air and fuel in a combustible mixture. This type of problem can be calculated with the equivalence ratio. Equivalence ratio states if the mixture is rich or lean. A rich mixture is given by equivalence ratio > 1 and a lean mixture is given by equivalence ratio < 1. This is calculated by stoichiometry of fuel and air, and actual fuel and air amount.

The equivalence ratio is an important parameter in combustion to state that a combustion is rich or lean. The equivalence ratio is dependent of the stoichiometry of the combustion. In this case methane is used as fuel. The stoichiometry of methane is given in Equation 4.1.

$$CH_4 + 2O_2 + 2\frac{79}{21}N_2 \rightarrow CO_2 + 2H_2O + 2\frac{79}{21}N_2 \tag{4.1}$$

The equivalence ratio is dependent of the stoichiometry mixture and the actual input (actual input of fuel and air in combustion). The formula for calculating equivalence ratio is given in Equation 4.2 [6].

$$\varphi = \frac{(m_{fuel}/m_{air})_{actual}}{(m_{fuel}/m_{air})_{stoichiometry}} \tag{4.2}$$

Where m is the mass.

In Figure 4.1 the relationship between the equivalence ratio and laminar flame speed is shown. By changing the equivalence ratio the diagram estimates the laminar flame speed for the given equivalence ratio.

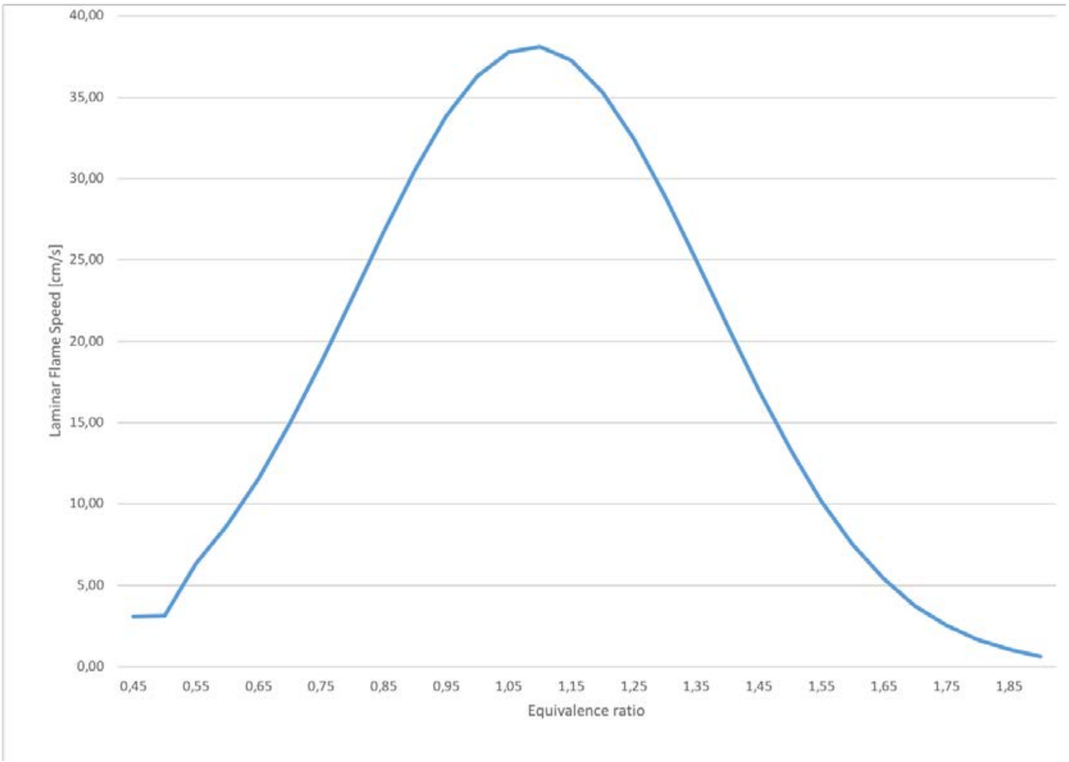

Figure 4.1: Relationship between equivalence ratio and laminar flame speed.

When the equivalence ratio is determined the laminar flame speed can be calculated. Many combustion applications are in need of an accurate method to calculate the laminar flame speed. The laminar flame speed is often given by detailed chemical kinetics which require a high level of computational skills. In [11] it is developed an algebraic formula based on the unburnt mixture, composition, temperature and pressure all of these parameters the laminar flame speed depends on. In this thesis this formula is given in Equation 4.3 and is used to calculate the laminar flame speed [11].

$$\delta_{L0}(\varphi) = ZW\varphi^{\eta}e^{-\xi(\varphi-\sigma)^2} \tag{4.3}$$

Where $\delta_{L0}(\varphi)$ is the laminar flame speed based on equivalence ratio. η, W and ξ are constants for a given fuel, in this case methane. Z = 1 when no mixing of fuel occurs. σ is a coefficient. Coefficients and constants are given in Table 4.1.

Table 4.1: Coefficients for laminar flame speed formula [11].

Fuel	**W [cm/s]**	$\boldsymbol{\eta}$	$\boldsymbol{\xi}$	$\boldsymbol{\sigma}$
$CH_4/\ C_2H_6$	38.638	-0.15	6.2706	1.1
CH_4/C_3H_8				

Mean flow velocity or bulk flow velocity is an important design parameter. The velocity is dependent of the radius of the burner thus this parameter is crucial when size of the burner is established. Since the velocity is dependent of the radius it will decrease as the area increase. The flame will settle where the local flow velocity is equal to the turbulent flame speed. The local flow velocity is highest at the end of the burner due to smallest radius this gives stable mechanism and prevent flash back of the flame. Blow off is prevented due to downstream velocity is lower than turbulent flame speed (where it settles). In Equation 4.4 the local flow velocity for a premixed flame is given.

$$U_\infty = \frac{\frac{\dot{m}_{air}}{\rho_{air}} + \frac{\dot{m}_{fuel}}{\rho_{fuel}}}{A} \tag{4.4}$$

U_∞ is the local mean flow velocity, $\dot{m}$ is the mass flow of both fuel and air. A is the cross-sectional area of the burner given by $A = \frac{\pi}{4} D^2$, where D is the diameter of the burner. ρ is the density of both fuel and air [12].

After the local mean flow velocity is determined it is easy to calculate the pressure drop across the burner. The pressure drop is wanted as low as possible which makes it an important parameter. Since the pressure drop is dependent on local mean flow velocity, the area (or radius) plays an important role to keep the pressure drop as low as possible. Evaluating the pressure drop can be done by Equation 4.5 [13].

$$\Delta p = \frac{1}{2} C_d \rho_{mix} U_0^2 \tag{4.5}$$

Δp is the pressure drop, ρ_{mix} is mixed density of fuel and air, U_0 is the local mean flow velocity at the start of the burner (burners exit) and C_d is drag coefficient. The drag coefficient is a tabulated values which for this case is assumed 0.6 [14]. The pressure drop difference between a high-swirl and low-swirl burner is presented in Figure 4.2

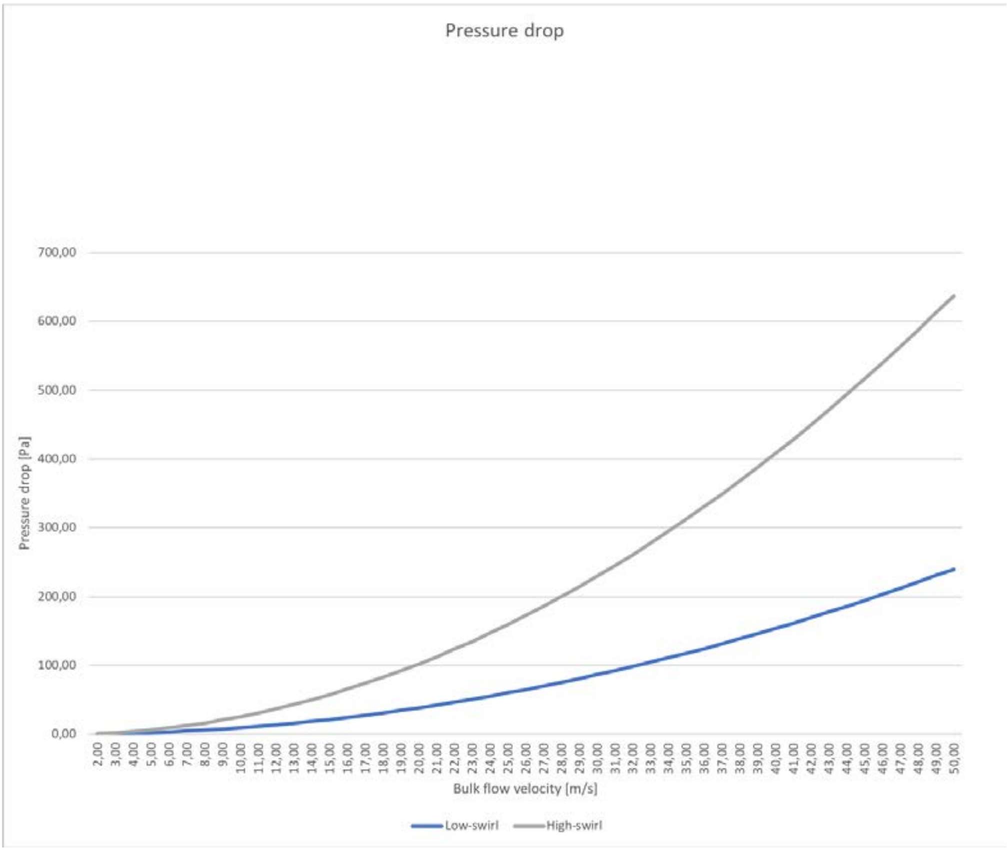

Figure 4.2: Difference in pressure drop for the two configurations.

The pressure drop difference between the high-swirl and low-swirl burner is simulated in excel to see if there is a difference. The basis for the simulation is the pressure drop formula given in Equation 4.5. The pressure drop is plotted for difference bulk flow velocities and the area difference in a low-swirl configuration compared to a high-swirl configuration. Due to closed center channel the pressure drop would increase due to a smaller exit area.

Swirl number is essential to determine the amount of swirl in a given burner. The swirl number is the ratio of angular momentum to axial momentum where the composition flows. In a low-swirl case the swirl number is typically between 0.4-0.6. The swirl number between 0.4-0.6 is a key parameter to operate in low-swirl condition. The stabilization mechanism in a low-swirl case is the divergent flow from a freely propagating turbulent flame [15]. In Equation 4.6 the formula for calculate the swirl number is given [12], [15], [16].

$$S = \frac{2}{3}\tan\alpha \, \frac{1 - R^3}{1 - R^2 + [m^2(\frac{1}{R^2} - 1)^2]R^2} \tag{4.6}$$

S gives the swirl number and α is the vane angle. R and m is ratio of the center region and annulus region for both radius and mass flow. $R = \frac{R_c}{R_b}$ where R_c is radius of the centerbody and R_b is the burner radius. $m = \frac{\dot{m}_c}{\dot{m}_a}$ where $\dot{m}_c$ is mass flow through centerbody and $\dot{m}_a$ is the mass flow through annulus [16]. In this thesis $\dot{m}_c$ is defined as % blockage of the burner area to find the optimal swirl number of the burner presented in Figure 4.3

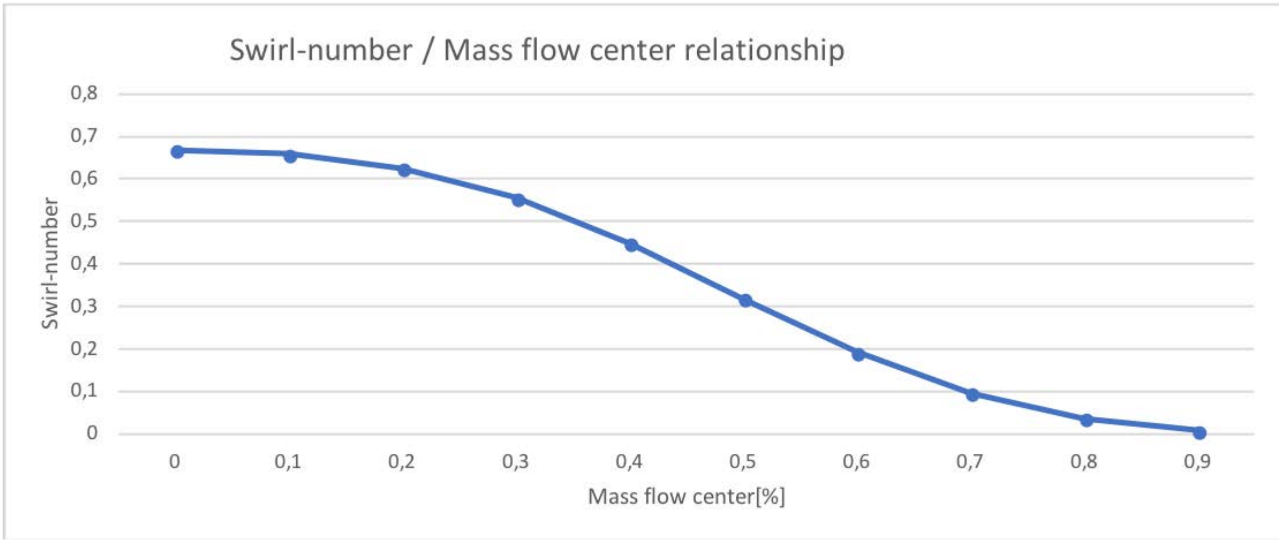

Figure 4.3: Swirl-number vs the mass flow in the center region.

For the burner used at Wärtsilä the burner design was unchangeable. This makes some limitations for the swirl-number calculations. The radius ratio was 0.69 due to the burner design. For the experiments conducted and used in this relationship between the swirl-number and mass flow in the center region the vane angle was 38º. Hence, the only changeable parameters were the blockage ratio differentiated by number of holes in the center plate. The plate design used was 100-, 110- and 120-holes. This design led to a blockage area from 35-44% in the center region. Use of this design the optimal swirl-numbers where calculated to be between 0.4-0.5.

Turbulent flame speed is an important mechanism of defining a low-swirl burner flame. The turbulent flame speed and local flow velocity defines the point where the flame settles. This means that the turbulent flame speed and local flow velocity is equal in a point where the flame settles. From this point the local flow velocity is decreasing and the turbulent flame speed is increasing. This means that the local flow velocity is higher than the flame speed velocity close to the burner and smaller after the stabilization point. The flame does not flashback to the burner due to the local flow velocity is higher close to the burner and it does not blow off due to the flame naturally settles in the center non-swirling point. The low-swirl burner gives a good stabilization of the flame due to the phenomena as mentioned [15]. Turbulent flame speed formula is given in Equation 4.7 [17], [15].

$$S_T = S_L + KI \tag{4.7}$$

Where S_T is the turbulent flame speed and S_L is the laminar flame speed. K is a constant which for methane-air flames is around 1.73 [15]. I is the turbulence intensity that will be shown how to calculate in Equation 4.9 [15]

Laminar flame thickness is the length of the reaction zone (flame) which is an important parameter used further in the calculations. The laminar flame thickness is usually only a few millimeters and is the zone before the products from the combustion [6]. The laminar flame thickness is given in Equation 4.8.

$$\ell_F = \frac{D}{\delta_L} \tag{4.8}$$

ℓ_F is the laminar flame thickness and δ_L is the laminar flame speed. D is diffusivity and is estimated to 0.200 cm^2/s from [18], [19].

Turbulence intensity is defined as level of disturbance in the outer flow [20]. The turbulence intensity is an important parameter but hard to calculate. In this thesis this parameter is made out of assumptions based on values given in CFD-online [21]. The burner operates in three configurations which is presented below.

- Low-swirl, lifted flame, turbulence intensity is assumed 2%.
- High-swirl, closed center section, turbulence intensity assumed 10%.
- Change from high- to low-swirl configuration, turbulence intensity assumed 20% (this configuration will be called “combined” in the calculations).

These values for the turbulence intensity is the basis for the calculations done in this thesis. According to CFD-online 1-5% is a medium turbulent case and 5-20% is a high turbulent case. High turbulence cases are typically complex geometries or flow inside rotating machinery. Medium turbulence case is low speed flows and less complex geometry such as pipes. This is the basis for assumptions done in this thesis [21].

The low-swirl burner is assumed as a medium turbulent case due to a lifted flame where the speed flow is much lower than close to the burner. The high-swirl burner is assumed to be a high turbulent case due to an increased speed flow. The flame is attached to the burner which means that unlike the low-swirl the bulk flow velocity would not decrease before the flame settles. Last scenario is the change from high-swirl to low-swirl. In this case the center channel is open and the flame would settle at the exit of the burner before the flame accomplishes a stable lifted flame. In this configuration it is a geometry change of the burner which could increase the turbulence intensity. This thesis only contains collected data for low-swirl configuration. Due to this a theoretical model of the high-swirl and back to low-swirl is used to see if there is a difference in the analysis. The basis for the calculations is the same as for the low-swirl therefore the only thing that is changed is the turbulence intensity.

Turbulent kinetic energy gives an indication of strength of turbulent in the flow. This implies that the higher turbulence in the system the more kinetic energy is available in the eddies [22]. The calculation model for turbulent kinetic energy is given in Equation 4.9 [23].

$$\varkappa = \frac{3}{2}(U_\infty * I)^2 \tag{4.9}$$

$\varkappa$ is the turbulent kinetic energy and U_∞ is the local flow velocity. I is the turbulence intensity.

The next formula to be implemented is the turbulence length scale ℓ. The turbulent length scale is the size of the large eddies in the system that contain the energy in turbulent flows. The turbulence length scale is restricted by the size of the duct due to the eddies cannot be larger than the duct in a fully-developed flow. This estimation is given in Equation 4.10 [23].

$$\ell = 0.07D \tag{4.10}$$

D is the diameter of the duct. In low-swirl and the case where it changes from high- to low-swirl the whole duct is the diameter. For high-swirl case the diameter is the annulus opening.

The root-mean-square velocity (rms-velocity) term defines the local turbulent flow field. By using the turbulent kinetic energy, it can be given algebraic like Equation 4.11 applies [24].

$$v' = \sqrt{\frac{2}{3}\varkappa} \tag{4.11}$$

v' is the root-mean-square [24].

The parameters given earlier are to be used in different turbulent models to investigate flame behavior. Therefore, the turbulent Reynolds number, turbulent Damköhler number and turbulent Karlovitz number is presented.

The turbulent Reynolds number gives an indication of the interactions of the eddies with the combustion processes and is given by Equation 4.12. For a turbulence case it requires that the Re_t > 1 and often Re_t >> 1 in practice [22] [24].

$$Re_t = \frac{v'\ell}{S_L\ell_F} \tag{4.12}$$

Where Re_t is the turbulent Reynolds number. v' is the turbulence intensity and ℓ is the characteristic length. S_L is the laminar flame speed and ℓ_F is the laminar flame thickness [24].

The dimensionless parameter turbulent Damköhler number is another important parameter. Damköhler number evaluates the how fast the fluid is mixing given as a mixing rate and the chemistry reaction rates. In a case where the chemical reaction rates are faster than the fluid mixing rate Da_t >> 1. For a reverse case Da_t << 1. For Da_t >> 1 the system is fluid mixing controlled and for a situation where Da << 1 the system is reaction controlled. For a case where the Da_t is approximately 1 it is controlled by turbulence and chemical kinetics. The Da_t number is given in Equation 4.13 [22] [24].

$$Da_t = \frac{S_L \ell}{v' \ell_F} \tag{4.13}$$

Da_t is turbulent Damköhler number. S_L is the laminar flame and ℓ is the characteristic length. v' is the turbulence intensity and ℓ_F is the laminar flame thickness.

The Karlovitz number is another parameter that is used in an analysis of the flame structure. This is a stretch factor that is defined as a dimensionless number that indicate the flame stretch [22]. The turbulent Karlovitz number is given in Equation 4.14 [25].

$$Ka_t = \frac{Re_t^{0.5}}{Da_t} \tag{4.14}$$

Where Ka_t is the turbulent Karlovitz number and Da_t is the turbulent Damköhler number and Re_t is the turbulent Reynolds number [25].

From the low-swirl data given in Chapter 6 this will be evaluated in a Borghi diagram to see what combustion regime the flame has. As mentioned it is assumed different turbulence intensities which gives different values for the Re_t, $Da_t$and Ka_t. This will be investigated analytical by only change the turbulence intensity to see if the different configurations of the burner have different flame regimes. Due to the change in configurations this will give a change in swirl-number between low-swirl and high-swirl that would be interesting to see if they end up in two different flame regimes in the Borghi diagram.

5 Emission

All industries that consider a new technology today should evaluate the emission aspect. The challenge in the shipping industry is the limited space available. The vessel is designed to do the job required, transportation. Everything from container vessel to LNG vessel has their unique design suited for the job. Therefore, when new technologies are considered the ultimate challenge is to find something that can be implemented in already existing vessels.

5.1 NO_x and CO

The shipping industry is one of the major contributors to the world NO_x emission and 70% of the shipping traffic is near land this contributes to high level of air pollution [26]. Methane is a greenhouse gas that contributes to the global warming and is the primary component in natural gas [27]. CO is another problem for the shipping industry when it comes to emission [26]. Shipping LNG could potential include all three of the mentioned gases. CO is in large quantity deadly and methane is one of the worst greenhouse gases [28], [27]. NO_x is a gas that plays a major role in producing smog [29]. The shipping industry has to take this seriously because the ships are inside harbors and close to cities during a trip. When handling LNG this involves all these gases and is needed to be handle carefully. The boil-off gas is pure natural gas (almost pure methane) and is in need of a technology that can handle it. As earlier described it is already existing technology for boil-off gas handling but Wärtsilä wants to improve the technology offered today and is now looking into the combined high/low-swirl technology.

In Figure 5.1 a historical and predicted trend on the NO_x and CO content is presented. This shows that the NO_x emission has increased and will continue to increase if nothing is done. It also shows that the NO_x emission is the main contributor to emission inside the shipping industry. The CO content is “low” because of the emission methods used today is sufficient to control the CO emission even though it always has to improve [26]. Pure methane (natural gas) will be a problem if tanks are ventilated or under other circumstances is freely propagating into the environment. As earlier showed the NO_x is temperature dependent and increases if the temperature increase. The combustion processes tendency to have high temperatures. To reduce the NO_x emission the temperature in combustion has to be reduced.

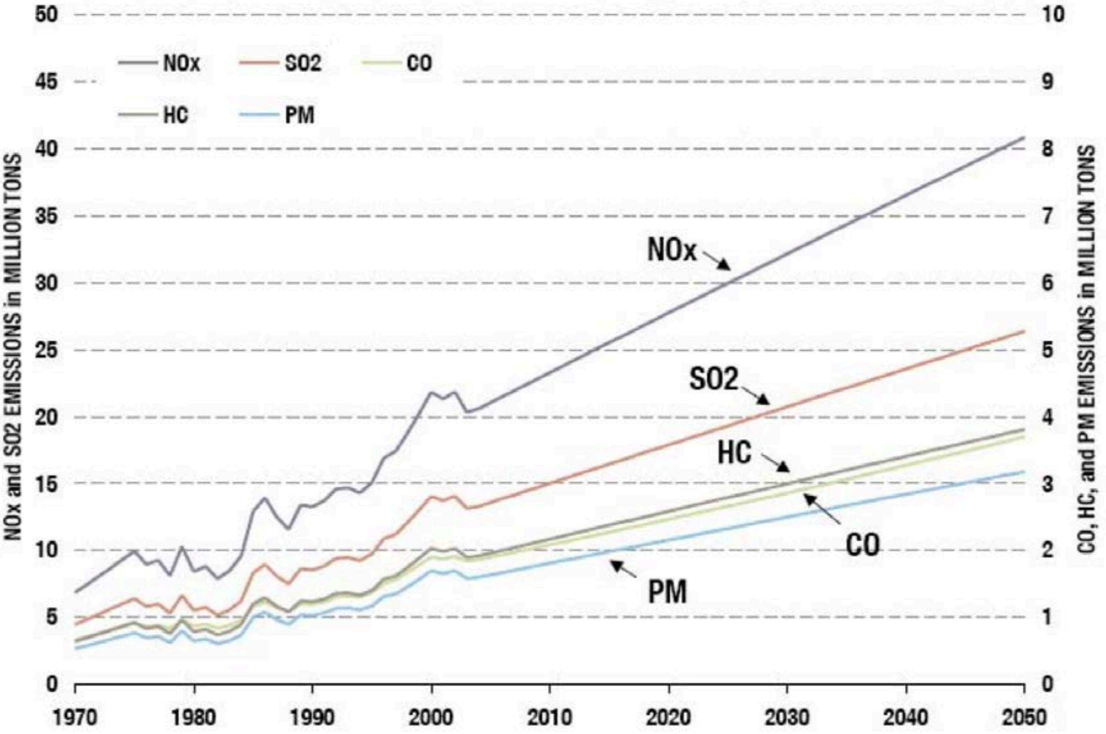

Figure 5.1: NO_x and CO emission from shipping industry [26].

As seen in Figure 5.1 the NO_x content is high and is increasing but this figure does not show NO_x emission from boil-off gas. This is emitted gas from the whole industry. It is shown to state that emission from the shipping industry is increasing and that technology that could reduce it is required. In this thesis the fuel onboard a vessel and the emission connected to propulsion systems is not investigated but if it is possible to reduce emission from boil-off gas it would make an impact on the whole industry.

In Figure 5.2 the correlation between the different types of NO_x is presented. A short description of the three of them is given under.

- Prompt NO_x is usually the NO_x type that counts for the smallest amount of NO_x. This type of NOx mainly occurs in rich composition. This type of NO_x is not taking into account in this thesis due to lean combustion.
- Fuel NO_x is a reaction product from fuel bound nitrogen products. This type of NOx does not occur when natural gas (methane) is the product and will therefore not be discussed further in this thesis.
- Thermal NO_x is the last type of NO_x showed in Figure 5.2. This type of NO_x usually accounts for the biggest amount of NO_x in combustion processes. From Figure 5.2 it is shown that the thermal NO_x increase rapidly due to increased temperature which indicates that the combustion temperature should be tried to keep low [30].

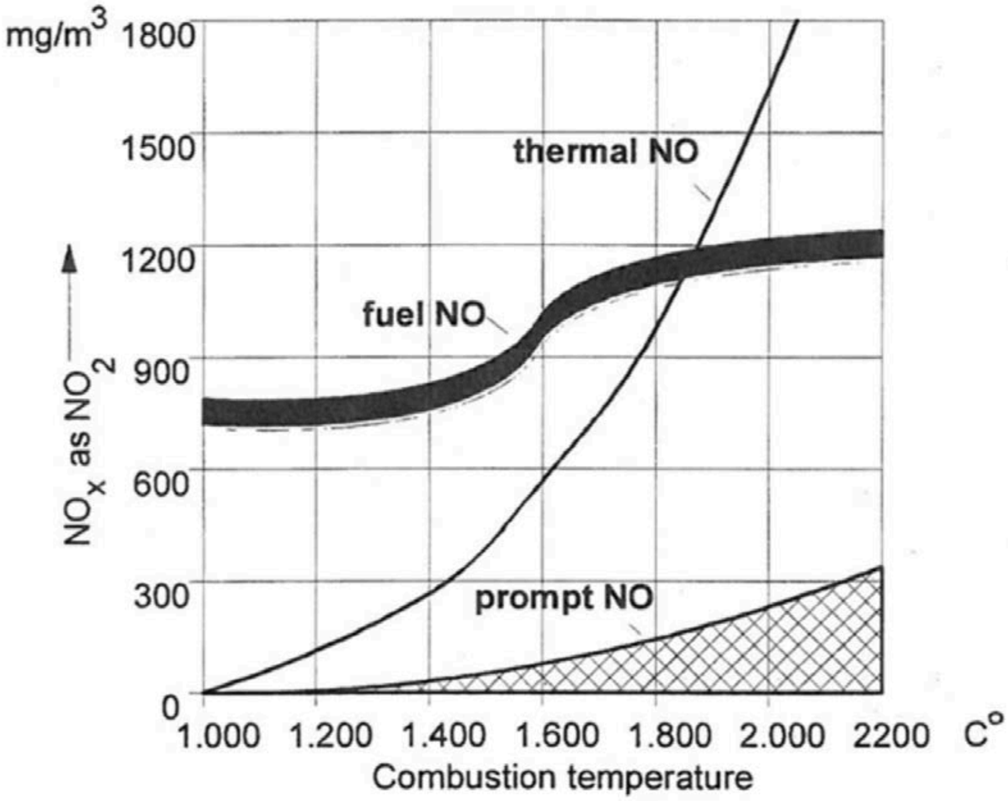

Figure 5.2: Different types of NOx [30].

The new boil-off gas technology has showed promising lab results and could be a contributor to reduce the NO_x emission [4].

Figure 5.3 shows an indication of the NO_x and CO emission from both high-swirl and low-swirl burner. Especially NO_x emission is remarkably higher in a high-swirl burner compared to a low-swirl burner. This is why Wärtislä has found the low-swirl burner interesting due to potentially low NO_x emission from boil-off gas.

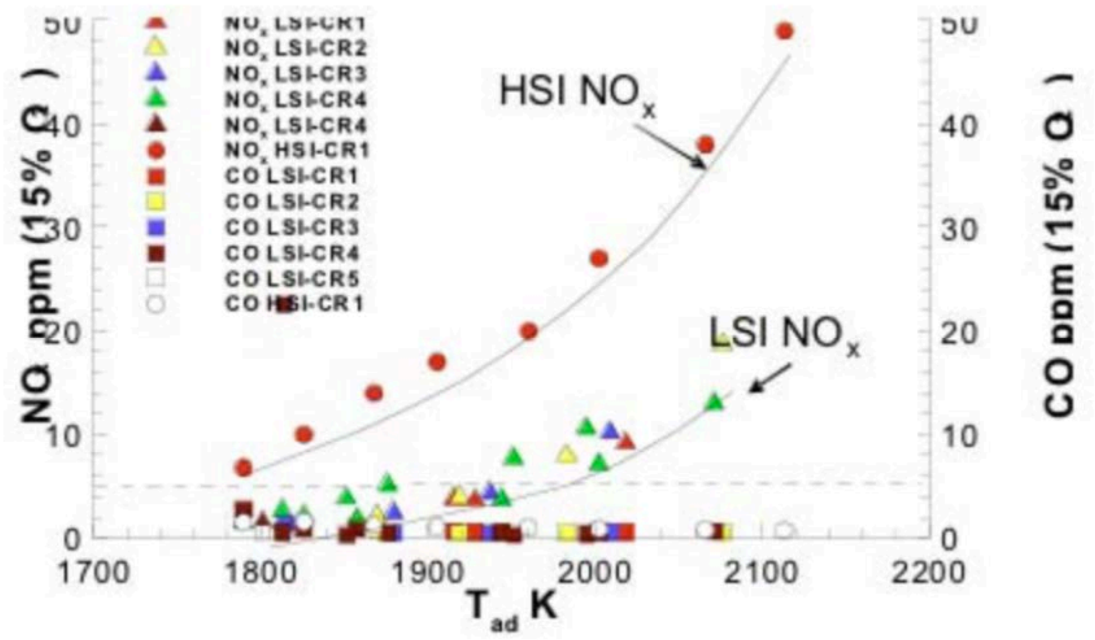

Figure 5.3: Indication of the difference in emission from high-swirl burner comapre to a low-swirl burner [4].

Figure 5.3 is not the figure of best quality, however it shows that the low-swirl burner is able to reduce the NO_x emission compared to a high-swirl burner. It also shows that is temperature dependent to be able to achieve low NO_x values.

From the measured values in Figure 5.4 it shows that a low-swirl burner could achieve NO_x emission numbers around 5ppm. This is far lower than a conventional high-swirl burner as shown in Figure 5.3. The aim in this thesis is not to reduce the emission from the low-swirl burner but is an interesting parameter that has to show decent results due to strict emission demand. Therefore, emission results from the test-rig is presented in this chapter since it links up to the theory presented. In the experiments done at Wärtsilä it was important to measure the emission to investigate if it was possible to achieve such low NO_x emission. In Figure 5.5 emission measurements from the experiment is shown. It shows that for a stable process (low-swirl operates at stable air and gas input) the NO_x is low. The CO content is also low under stable operation.

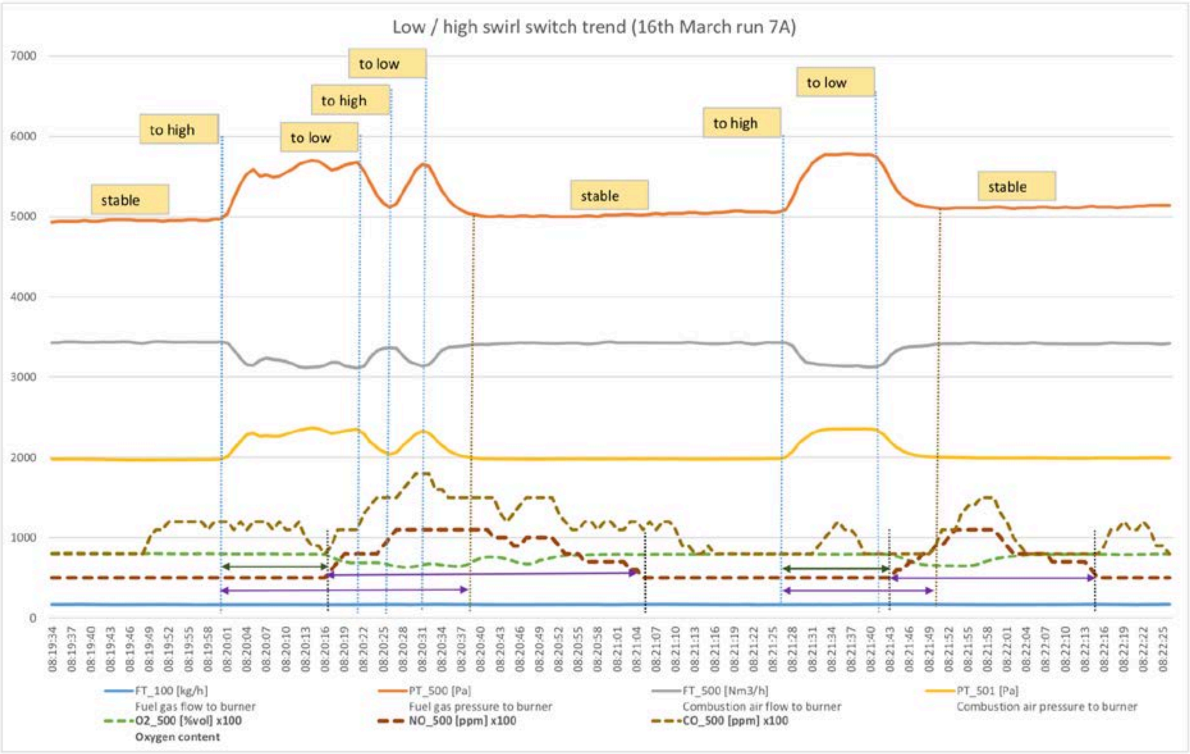

Figure 5.4: NO_x emission measurment from test-rig at Wärtsilä.

The reason why the NO_x and CO increase is when the system increases inlet of gas and air. The CO and NO_x shows low and promising results under stable operation. To give an indication of how hot it is an image from the rig is presented in Figure 5.6.

Figure 5.5: Test run with combustion chamber. Indication of heat release from the burner.

In this test run the NO_x increased due to heat of the combustion chamber which heated up the flame. The system is in need of some cooling device to keep the temperature down. In Figure 5.7 the temperature of the combustion chamber is measured to be around 950ºC (up in left corner of the camera) which gives a good indication that the system is in need of a cooling device.

Figure 5.6: Temperature measured in combustion chamber.

To meet the strict emission demand from authorities the system shows that it is capable of operating with a very low NO_x content emitted. An improvement of the system would be to install a cooling device on the combustion chamber to keep the temperature down. This was not possible during the experiments but should be considered before implementation in a vessel.

6 Results

In this chapter the results from the research done at Wärtsilä test rig will be analyzed and connects theory to the practical experiments. The experiments were done at Wärtsilä Moss test rig and was a large-scale experiment of the burner. The test rig was a large-scale test-rig where the dimensions was like they are intended to be onboard a vessel. The high-swirl burner was tested with the same premix as the low-swirl burner and not as it should in a real situation.

This chapter is divided into four chapters. Chapter 6.1 contains a description of the experiments. Chapter 6.2 provides the results from the first experiment. Chapter 6.3 contains results from the experiments and an analysis of the experiment. Chapter 6.4 presents experiments done by Wärtsilä but is shown to amplify the results found.

The task description states that the experiments will be held at Wärtsilä, unfortunately it turned out to be just two trips. There was no possibility to make changes through the experiments which implies that it was not possible to make an impact on the experiments or try to change different parameters.

Wärtsilä Moss had an "engineering approach" to the experiments conducted, meaning that several experiments were conducted where different parameters were adjusted before analysing the results. As the task description applies, the most important thing is to find a correlation between flame shape and swirl number.

6.1 Experiment description

Experiments was done at Wärtsilä Moss test rig and was large-scale experiments. The rig was connected with gas supply (methane) and air supply which entered a premix unit. This well-mixed composition was entered the burner which was ignited to start the combustion. The intention was to see if it was possible to go from a low-swirl configuration over to a high-swirl configuration and back to low-swirl. This mechanism is what is unique with the system and is the main thing it has to be able to do before further research. If this worked out further research should include an analysis of the flame to be able to control it and important design parameters to get an optimal burner. The first experiment described in Chapter 6.2 was to verify that the combined high/low-swirl burner worked as intended. Since it has never been done before it was important that it was possible to combine a high- and low-swirl burner into one burner.

In the second experiment the burner was tested with a quarl of different dimensions which should help on the stabilization of the flame. The quarl makes an impact on noise and NO_x emission as well but in this thesis only the stabilization impact from the quarl will be discussed [31].

The intention was to use a high-speed camera (described in Chapter 6.2) to collect data and by high-speed films get an idea of recirculation zone and dimensions of the flame. This together with calculated values would give a good indication of how the flame behave. Since the data collected was not as useful as hoped the data used in this thesis is provided from Wärtsilä. The data gathered from Wärtsilä is the gas and air supply to the burner which will be used for calculations. The design of the burner is also given. Images from a thermal camera is used as the basis for the flame shape and to see if the low-swirl flame shape is achieved. To be able to see if the burner operates as a low-swirl burner the most important thing is that the flame shape is as described earlier, lifted off the burner.

In the first experiment, different number of holes were tested in the centerplate. Three alternatives were available, 100, 110 and 120 holes. These plates differentiate the blockage ratio. Since the radius ratio does not change, all of these plates give a swirl-number that only is adjusted by the centerplate.

In the second experiment a 100-hole plate was chosen and different sizes of quarl. The 100-plate had showed that it was possible to change between high- and low-swirl therefore the only thing that was changed was the conical expansion. 100-hole plate had showed that a stable flame occurs thus the unknown parameter was the conical expansion was the only thing that was changed. The test will give an indication of how the flame behave with a conical expansion.

6.2 Practical experiments

Two trips to Wärtsilä Moss test rig to gather data for the analysis has been done. It was used high-speed camera (Photron APX RS) to get an indication of recirculation zones and dimensions of the flame. The data for the experiment is given in Table 6.1.

Table 6.1: Test data for the first experiment.

Swirl-type	Number of holes	Vane angle	Radius ratio	Swirl-number
Low-swirl	120	38	0.69	0.4
High-swirl	Closed	38	0.69	0.67

The swirl number is calculated by equation 4.5. The total blockage in the center channel was 44%. Since the burner design is the same for all experiments this will be constant. According to work done by Cheng these values is inside the range. Based on experiments done by Cheng these parameters are inside the range of what is ideal. The vane angle should lay between 37°-45° and the radius ratio between 0.5-0.8 [4]. The swirl number range is different for a low-swirl compared to a high-swirl. The only parameters that changes in the equation is that the mass flow ratio disappears due to closed center section in the burner. Therefore, the swirl-numbers for the two burners configuration is different even though the burner design is the same. The swirl-number for a low-swirl case should be in the range of 0.4-0.55. For a high-swirl configuration it should be between 0.6-1.6 [10].

In Figure 6.1 it is shown a characteristic low-swirl flame shape that indicates that Wärtsilä is able to run the burner in a low-swirl configuration. In the image it shows areas with a more yellow color, this due to treat of the materials with Copaslip (material protection in high-temperature environment).

Figure 6.1: Low-swirl flame shape

In Figure 6.2 it is shown the same run and that it still has a low-swirl flame shape. This indicates that the flame is stabilized in low-swirl configuration.

Figure 6.2: Low-swirl flame shape

From this experiment it is shown that it is possible to run the large burner in a low-swirl configuration. This is a combined high/low-swirl burner which makes it important for the burner to change between low-swirl configuration and high-swirl configuration. Figure 6.3 shows a high-swirl flame shape. The center channel is now closed.

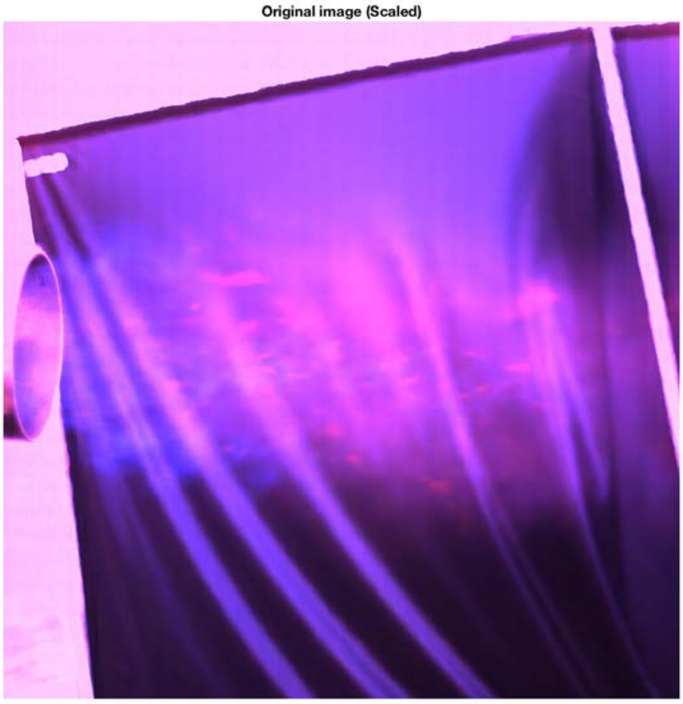

Figure 6.3: High-swirl flame shape

The high-swirl flame is as earlier described attached to the burner. The flame is elongated and does not have the same flame shape as a low-swirl flame. This flame looks more like a jet flame (cylindrical shape) while the characteristic low-swirl flame is more concentrated (spherical shape).

Even though it is not possible to make any analysis on the data gathered a major finding is that it is possible to combine low- and high-swirl in one burner. The experiment confirmed that it was possible to change from low-swirl configuration over to high-swirl configuration and back to low-swirl. This is what the burner is designed to do and has probably never been done before and inspires further research.

Due to daylight and bad background shield it was not possible to see anything of the images taken. Figure 6.1-6.3 shown in this report has been treated in Matlab written by Joachim Lundberg (Appendix B) which makes it possible to see flame shape but not recirculation zone or indication of flame dimensions. The biggest achievement in this experiment was to verify that the combined high/low-swirl configuration worked.

In the second experiment Wärtsilä Moss had done some improvements of the test rig. To be sure that the daylight and background problem was negligible they moved the test rig in a big steel tent. In Figure 6.4 the improved test rig is shown.

Figure 6.4: Test rig "house"

In this test facility the daylight and background shield problem were negligible due to the shielded test rig. Because of the heat generated from the burner it was not possible to have the high-speed camera inside the test rig which made it impossible to take high-speed films. The heat field outside was very strong as well hence it was impossible to use the high-speed camera. Since no data was gathered the test data used in the analysis is data from Wärtisilä Moss.

This experiment was conducted without a combustion chamber to be able to see the flame shape and that it was possible to change between the two configurations. From this experiment it was concluded that the burner could run in both low- and high-swirl but several experiment and analysis had to be done to verify the burner. One of the problem connected to the burner was the repeatability of change the burner configurations. Another problem that had to be sorted out was that this burner is going to have a combustion chamber connected which probably will make an impact on the behaving of the flame.

In the next experiment it was decided to connect a quarl to the burner. A quarl is an expansion that is meant to stabilize the flame due to insulation of the main flame [31]. This will be described closer in the next heading where the experiment with the quarl was conducted.

6.3 Analysis of data

As earlier stated the data is collected by Wärtsilä is the data used for the analysis. The basis for the analysis is the equations collected presented in Chapter 4. One of the main problems connected with this burner is that the theory is spread all over and due to limited time in the industry it has not been collected in the way done in this thesis. Therefore, one of the most imported and requested things is a model that can give an indication of what parameters that is critical and give an overview over parameters to change instead of testing the equipment by trial-and error. A major finding would be to connect the theory found to the experiments conducted and be able to find a correlation between swirl number and flame shape.

The burner was tested with a conical expansion (quarl) in different sizes as mentioned earlier and this is presented in Table 6.2

Table 6.2: Overview of experiment.

Experiment number	**Dimension of quarl (length)**
1	360mm
2	280mm
3	190mm
4	100mm
5	None

To make the conditions as similar as possible it was tried to find where both mass flow of gas and air are approximately the same. The data collected is given in Table 6.3. In this experiment the burner used a 100-hole plate. Vane angle of 38° combined with the burner design this gave a swirl-number of 0.5 for all experiments. This gives the mc to 35% of blockage which has previous shown that a low-swirl flame is possible.

Table 6.3: Gas- and air supply.

Experiment number	**Gas supply**	**Air supply**
1	$\dot{m}_f = 195\ kg/h$	$\dot{m}_a = 3827\ kg/h$
2	$\dot{m}_f = 194\ kg/h$	$\dot{m}_a = 3815 kg/h$
3	$\dot{m}_f = 196\ kg/h$	$\dot{m}_a = 3818\ kg/h$
4	$\dot{m}_f = 193\ kg/h$	$\dot{m}_a = 3800\ kg/h$
5	$\dot{m}_f = 194\ kg/h$	$\dot{m}_a = 3792 kg/h$

Since it is a large-scale test rig the values is not identical which is hard to achieve and was not the intention, therefore there is some difference but it is tried to find the most identical values due to it is the difference sized quarl that is important.

With these values the equivalence ratio can be calculated by Equation given in 4.2. As earlier described the equivalence ratio states if the mixture is lean or rich. The equivalence ratio is as stated in equation 4.2 dependent of the stoichiometry of the combustion. This is given in Equation 4.1 where methane is assumed as the used fuel.

The calculated values of equivalence ratio are given in Table 6.4.

Table 6.4: Calculated equivalence ratio.

Experiment number	Equivalence ratio
1	0.86
2	0.89
3	0.89
4	0.88
5	0.89

From these calculations it is seen that this is a lean mixture due to equivalence ratio < 1. The low-swirl burner is designed to operate under lean-premix condition to meet the strict emission regulations [4].

The laminar flame speed is calculated by Equation 4.3. Equivalence ratio presented in Table 6.4 was used as input in the formula.

Table 6.5: Calculated laminar flame speed.

Experiment number	Laminar flame speed $[cm/s]$
1	27.54
2	29.82
3	29.82
4	29.10
5	29.82

Equation 4.3 is an algebraic way of calculating the laminar flame speed. The formula contains a set of constants that has to be used. The values found by solving this algebraic seems accurate compared to previous work done by Cheng and Bédat [32].

The next parameters are calculated by the equations given in Chapter 4. These values are used in further calculations to determine the behavior of the flame. The characteristic length is constant for all experiments since the design of the burner is the same.

Table 6.6: Calculated values from equations presented in Chapter 4.

Exp.	$S_T\ [m/s]$	$\ell_f[m] * 10^{-5}$	I[%]	$\kappa[m^2/s^2]$	ℓ[m]	$v'[m/s]$
1	1.37	7.26	0.02	0.6	0.014	0.63

2	1.23	6.70	0.02	0.44	0.014	0.54
3	1.10	6.70	0.02	0.32	0.014	0.46
4	1.07	6.87	0.02	0.31	0.014	0.45
5	1.06	6.70	0.02	0.29	0.014	0.44

Next parameters that is calculated is the bulk flow velocity. In earlier experiments this value has been much lower for experimental research [32]. The design Wärtsilä chose gives a high bulk flow velocity compared to most of the earlier done research. The velocity is area dependent which means if Wärtsilä change the design the velocity would either increase or decrease. As earlier described the flame settles where the local flow velocity and turbulent flame speed is equal. A big difference in bulk flow velocity and turbulent flame speed demands a large area where the flame settles [15].

Table 6.7: Bulk flow velocity.

Experiment	**Bulk flow velocity $[m/s]$**
1	31.5
2	27
3	23
4	22.8
5	21.8

A figure that shows the relationship between local flow velocity and turbulent flame speed is presented in Figure 6.5. On the y-axis the local flow velocity is shown while the x-axis gives the position. Figure 6.5 shows that the flame settles where local flow velocity is equal to turbulent flame speed. It also shows that the local flow velocity decreases as the distance increase, this due to increased area. The turbulent flame speed increases as the turbulent increases after the settling point. This due to more turbulent condition after the settling point of the flame [15]. In this experiment the bulk flow velocity is high compared to earlier research. It has been done some work on industrial gas turbines where bulk flow velocities have been simulated up to 50 m/s. In this simulated gas-turbine they achieved a stable flame despite different equivalence ratios. The simulations also stated that it was possible to achieve very low NO_x emission despite industrial size gas turbines [10]. A simulation case is a "perfect world" where everything is stable such as machinery (design) and environmental impact.

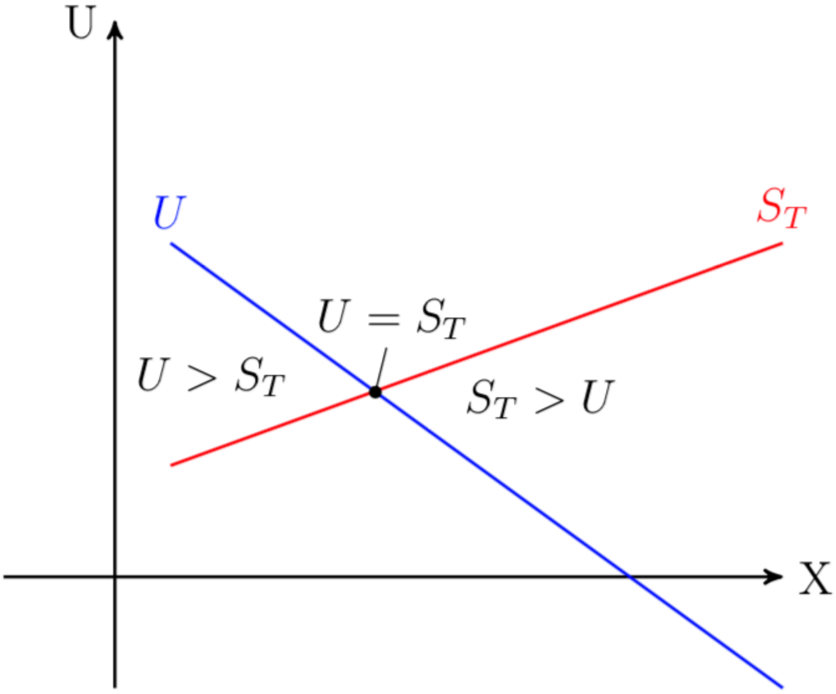

Figure 6.5: Stabilization mechanism of a low-swirl burner flame [15].

Figure 6.5 shows that the flame would settle where the turbulent flame speed equals local flow velocity. The turbulent burning velocity is independent of the bulk flow velocity. Therefore, a big difference between bulk flow velocity and turbulent flame speed gives that the flame settles further away from the burner. In this experiment the bulk flow velocity is very high (industrial size) and the turbulent flame speed is around normal with the given equivalence ratio and turbulence intensity. This gives that the flame either settles further away or is dependent of a large area where it settles.

In the first experiment a 360 mm quarl was used. This is first of all a mechanism that reduces noise (which will not be discussed in this report) but also gives an idea of how the flame will behave with an expansion (not the intension of the experiment). The low-swirl burner is going to be wrapped inside a combustion chamber when installed, thus the expansion would give an indication on how the flame behaves when it wrapped. From the images provided by Wärtsilä it is hard to accurately state a flame shape due the conical expansion. The expansion could provide a thermal reflection from the flame to the quarl thus it looks like the flame is attached to the burner. The flame shape of the first experiment is given in Figure 6.6.

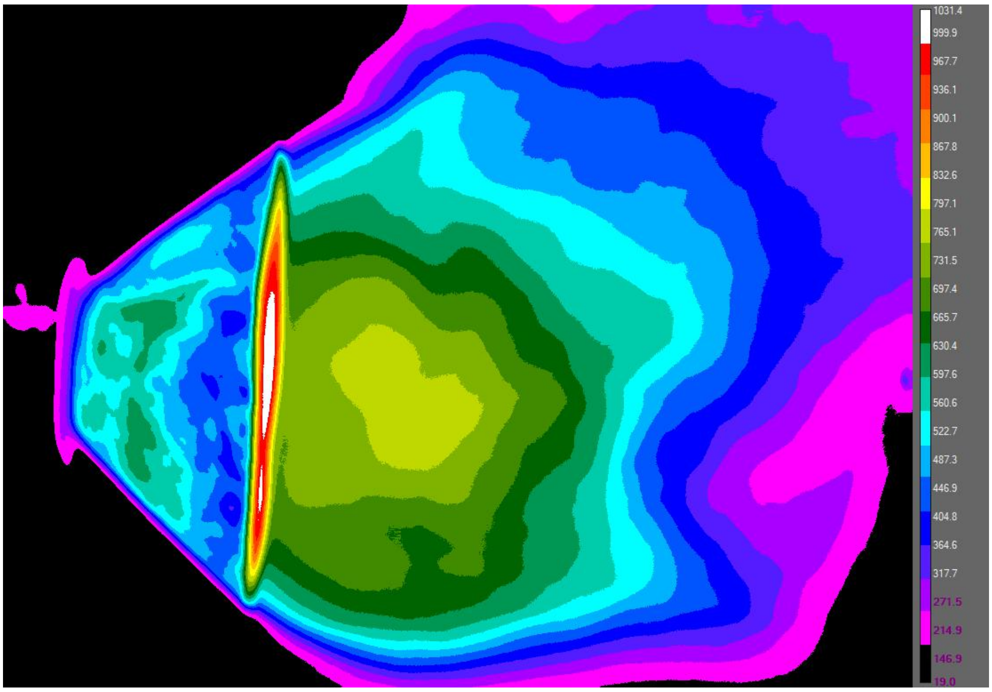

Figure 6.6: 360mm quarl

The purple area to the left is the burner and the purple “stripes” angled from the burner is the expansion. From this image it looks like the flame is attached to the burner. In this experiment the low-swirl flame shape (lifted flame) did not occur.

In the next experiment the quarl was modified to 280mm trying to achieve the characteristic low-swirl flame shape. In Figure 6.7 the result of the modified quarl is presented.

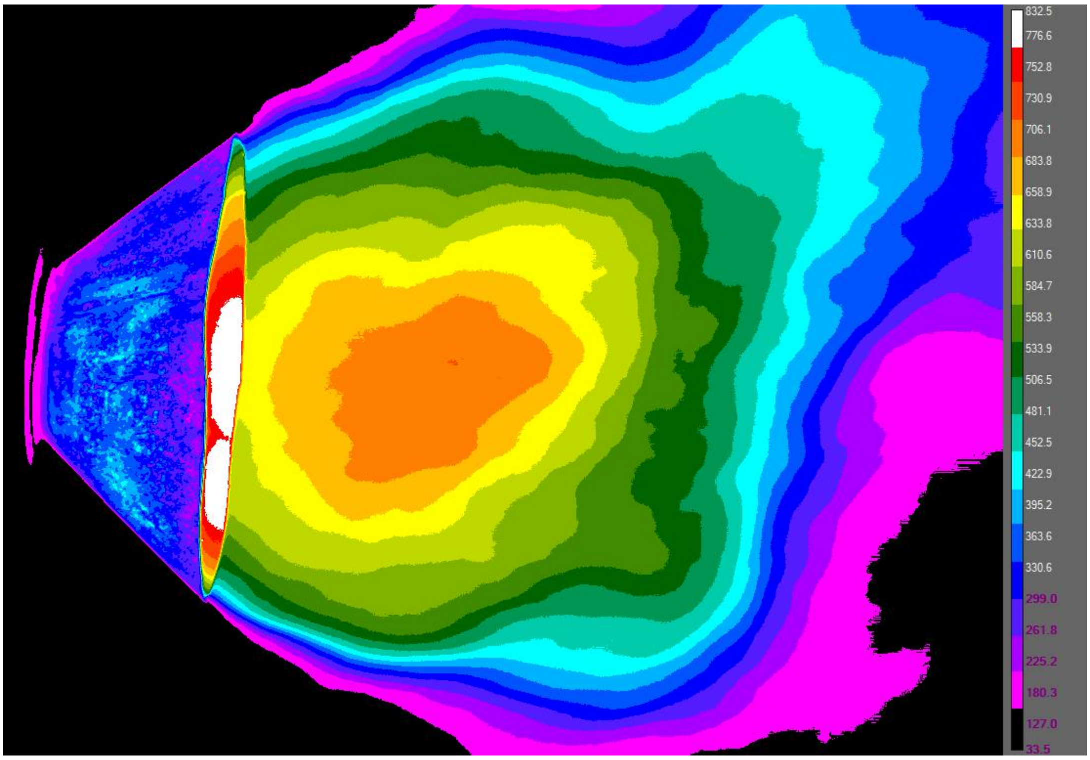

Figure 6.7: 280mm quarl

In this image the center of the flame has a spherical shape and could look like a low-swirl flame. It looks like the flame is in a preface of settling but is still attached. From the image it looks like the low-swirl flame did not settles and therefore a low-swirl flame shape did not occur. The interesting part is the flame shape that has a spherical shape that could indicate that it was close to settled.

In Figure 6.8 the quarl is modified to a dimension of 190mm. In this image something interesting happens. With the previous discussed thermal reflection from the expansion fresh in memory it could looks like the flame settles at the exit of the quarl. It seems like a characteristic low-swirl flame shape is achieved at the exit of the conical expansion.

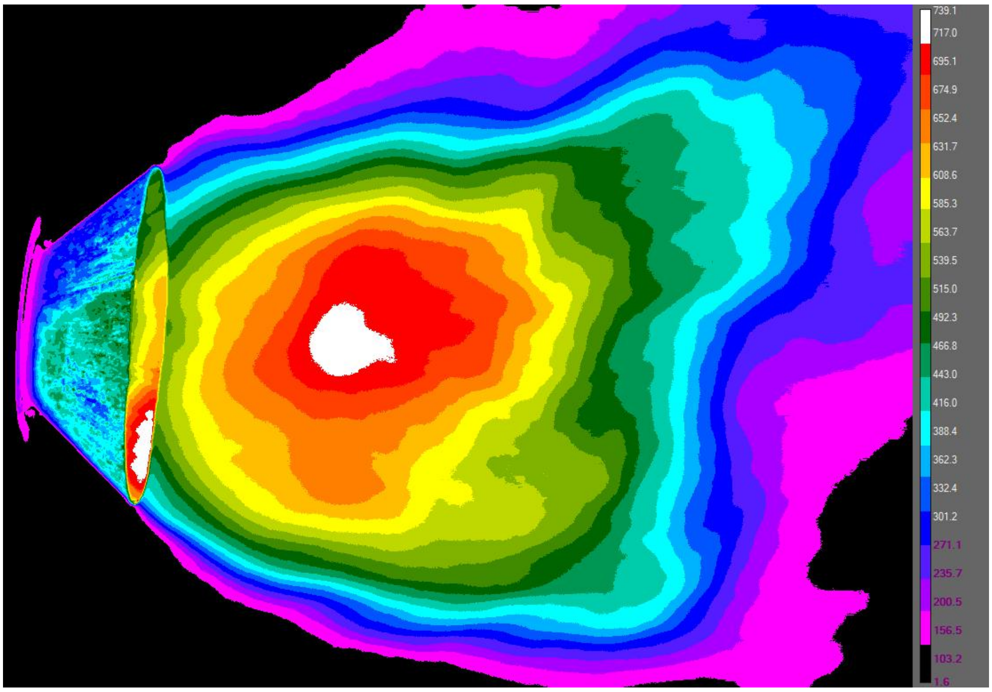

Figure 6.8: 190mm quarl

Inside the quarl it is a white dot which also occur in the flame at the outside. This gives an indication of that the quarl creates a thermal reflection that makes it difficult to state if the flame shape is a characteristic lifted flame. The flame shape is spherical and due to reflection, it is hard to say if the flame is lifted or not. It looks like the lifted flame is achieved.

Figure 6.9 reinforces the suspicion of reflection from the quarl. In this image it seems like the flame has settled just outside the quarl. Inside the quarl it looks like the flame is thermally reflected.

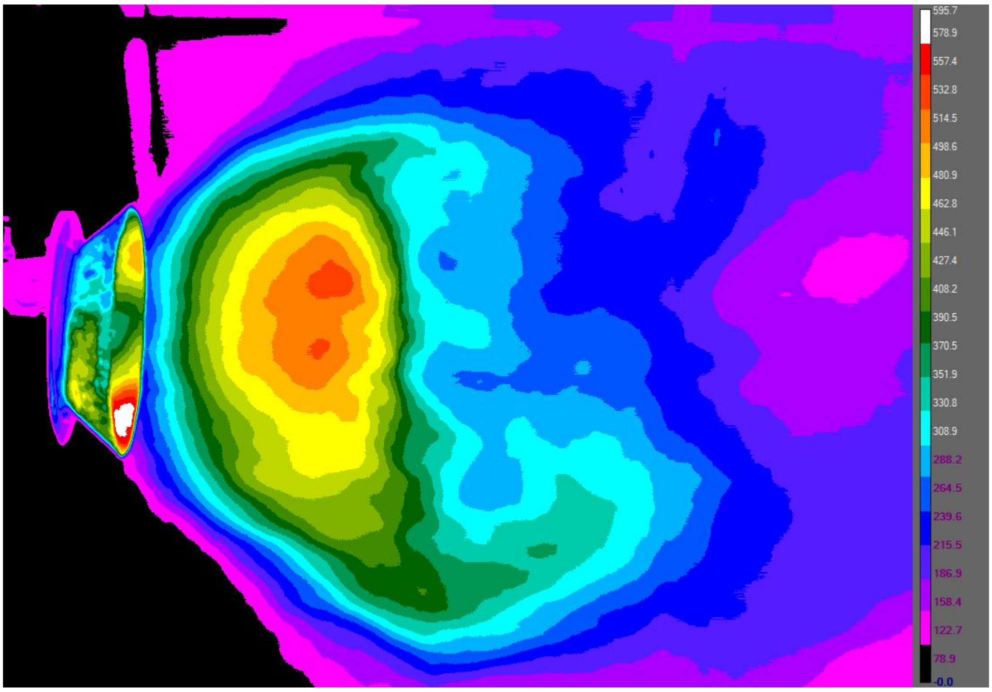

Figure 6.9: 100mm quarl

Right outside the quarl an indication of a lifted flame occurs. The flame has strange shape (not fully developed?) thus a conclusion due to the flame shape is hard to state. This implies the suspicion that the quarl reflects the flame and from an imaging point of view. In this experiment it looks like the characteristic low-swirl flame shape did occur.

From the experiments it is hard to state if the lifted flame did occur or not. A strong indication of a lifted flame is given from the quarl with the smallest dimension. A suspicion is that the flame is thermally reflected to the quarl thus give an indication that it is attached. Either way it shows that the flame behaves different with an expansion mounted on the burner. Important parameters that should be taking into account for further research is given below.

Area of the expansion is important due to the flame settles where the local flow velocity and turbulent flame speed is equal (the flame is in need of an area to develop a lifted flame). With such a big difference in bulk flow velocity and turbulent flame speed the flame diameter (where it settles) could be much larger than the burner diameter. Another parameter that should be investigated is the stoichiometry. Due to a wrapped flame this is quite different than a freely propagating environment. In earlier research air supply has been mounted to inject air which could be enough to get a lifted flame [32]. This type of problem would not be enlightened in this thesis.

In Figure 6.10 the same burner design and number of holes is used but the quarl is removed and the burner operates as in the experiment conducted with the high-speed camera. The exit of the burner is straight out in the environment and no closure.

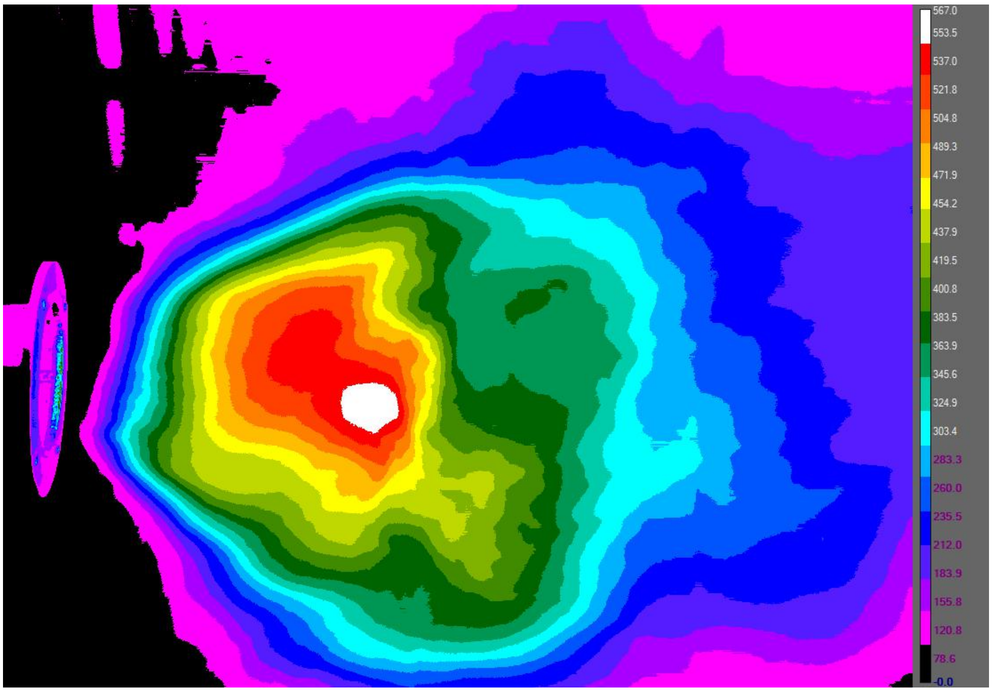

Figure 6.10: None quarl used

In this experiment the lifted flame and characteristic low-swirl flame occurs. The flame shape in this experiment is not very unlike the experiments done with a quarl. The main difference is that it is possible to clearly see that the flame is lifted and achieves the characteristic flame shape. The experiments shows jet again that a low-swirl flame shape is occurred and that the burner is able to operate as a low-swirl burner.

A switch between the low-swirl to high-swirl configuration was tested after the low-swirl flame was achieved. In Figure 6.11 the high-swirl flame with a closed center channel is given.

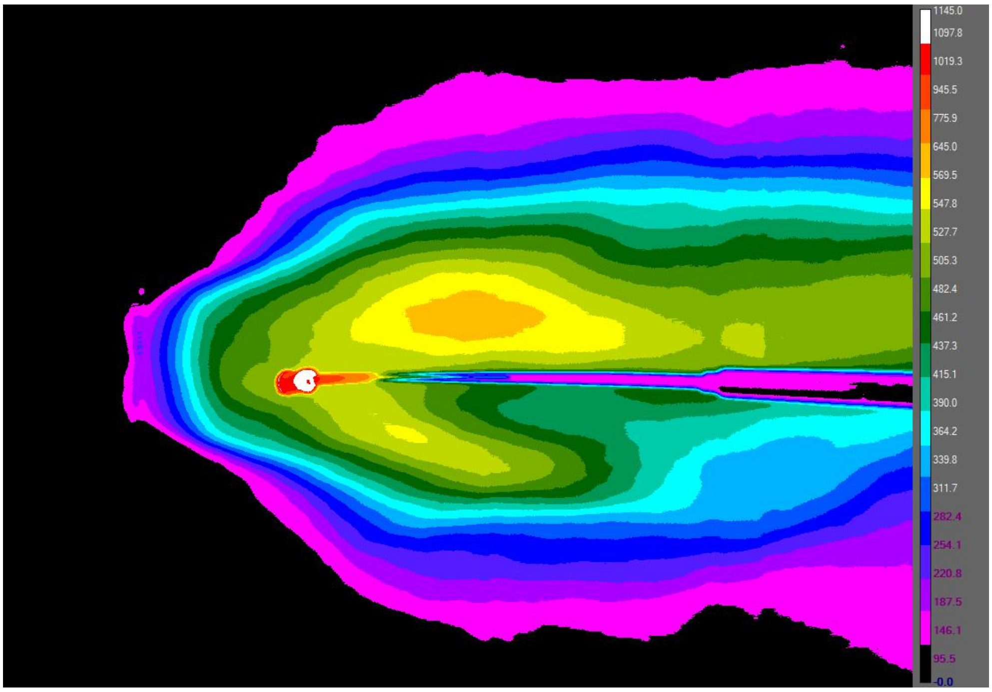

Figure 6.11: High-swirl flame

The high-swirl flame shape is more elongated (cylindrical shape) than the low-swirl flame and look more like a jet flame. In this case the swirl number was 0.67 with the center plate closed as the burner design was the same.

To able to analyze the flame turbulent- Reynold, Damköhler- and Karlovitz number are presented. This is calculated from the Equations 4.12-4.14.

Table 6.8: Calculated values for low-swirl configuration.

Experiment	Re_t	Da_t	Ka_t
1	441	84	0.25
2	378	115	0.17
3	322	135	0.13
4	315	132	0.13
5	308	141	0.12

The values calculated are reasonable compared to findings in a report written by Cheng and Bédat [32]. From the flame analysis there is nothing that give indications of why the low-swirl flame not occurs when the quarl is used. As mentioned earlier it is two important parameters that has to be evaluated in this case. The first problem is the area the flame needs. With such a high exit velocity the flame is either stabilized far away from the burner which could make it unstable or the flame is in demand of a large area according to Figure 6.5. Therefore, a design change could be a solution where a larger burner is used to decrease the bulk flow velocity. The other thing that should be considered is air supply to not break the stoichiometry of the combustion. The air condition changes in a closed environment which is why air supply should be considered. These two changes would not be evaluated in this thesis.

The turbulence intensity given Chapter 4 was stated in various scenarios of the burner. This would be interesting to analyze in a Borghi diagram to see if there is a difference in regimes. This would give an indication if the flame would behave different in the different scenarios. This would give a good indication of the correlation between the swirl number and flame shape. For the low-swirl burner the swirl number is still 0.5 and for the high-swirl burner it is 0.67.

For the high-swirl burner the integral length scale uses a hydraulic diameter of 60mm due to the center channel is closed and only the annulus is open. New values are calculated to see if there is a difference when increasing the turbulence velocity. The data is given in Table 6.9.

Table 6.9: Data for different scenarios.

	High				**Combined**			
Experiment	I	κ	ν'	S_T	I	κ	ν'	S_T
1	0.1	14.9	3.15	5.73	0.2	59.5	6.3	11.18
2	0.1	10.9	2.70	4.97	0.2	43.7	5.4	9.64
3	0.1	7.9	2.29	4.26	0.2	31.7	4.6	8.26
4	0.1	7.8	2.28	4.23	0.2	31.2	4.6	8.25
5	0.1	7.1	2.18	4.07	0.2	28.5	5	8.95

This gives very different values compared to the low-swirl burner case. Both of these cases are more turbulent due to an increase in turbulence intensity. Such a difference in turbulence could be used to describe the correlation between swirl number and flame shape. The Borghi diagram contains different regimes which is used to describe combustion flames.

The new data calculated is shown in Table 6.10 and is the data that is going to be used in the Borghi diagram.

Table 6.10: Data for the Borghi diagram.

	High			**Combined**		
Experiment	Re_t	Da_t	Ka_t	Re_t	Da_t	Ka_t
1	662	5	5	4411	8.5	8

2	568	7	3.5	3784	11.5	5.5
3	481	8	3	3223	13.5	4
4	479	8	3	3221	13	4.5
5	458	8.5	2.5	3504	12.5	5

Both of these cases are within the turbulent specte due to Re_t > 1 and actually Re_t >> 1. The Da_t is decrease a lot compared to the low-swirl case which indicates less stretch. The Ka_t > 1. These parameters summed up gives a new combustion regime.

To evaluate the numbers from the calculations a Borghi diagram is chosen. The Borghi diagram is a method of evaluate the combustion regime. In this thesis the values have been calculated analytical with some assumptions made which could lead to inaccurate values. However, it is an interesting analysis due to the configuration difference in the burner. In the y-axis the rms-velocity and laminar flame speed is the basis which is the intensity of turbulence in the flame. On the x-axis the turbulent length scales relationships create the basis.

The first parameter is to evaluate if the flame is turbulent or laminar. If the turbulent Reynolds number is less than 1 it is a laminar flame and if it is above it is in the turbulent regime. From the calculations done Re_t >> 1 which indicates that this is inside the turbulent regime for all cases.

In the corrugated flamelet zone the flame propagates as a surface containing large scale wrinkles. In the thin reaction zone the flame could “split” into different pockets containing reactants only, products only or a mixture of both [33].

It is boundaries connected to the diagram which will be explained. In the corrugated area the Da_t number >> 1 and Ka_t< 1. In the thin reaction zone the Da_t > 1 and Ka_t > 1.

As for the theoretical assumptions made for the three cases it would be interesting to see if it appears in different combustion regimes. As seen in Figure 6.12 the flame structure of the low-swirl flame is inside the corrugated flamelets. The high-swirl flame and the combined flame is inside the thin reaction zone.

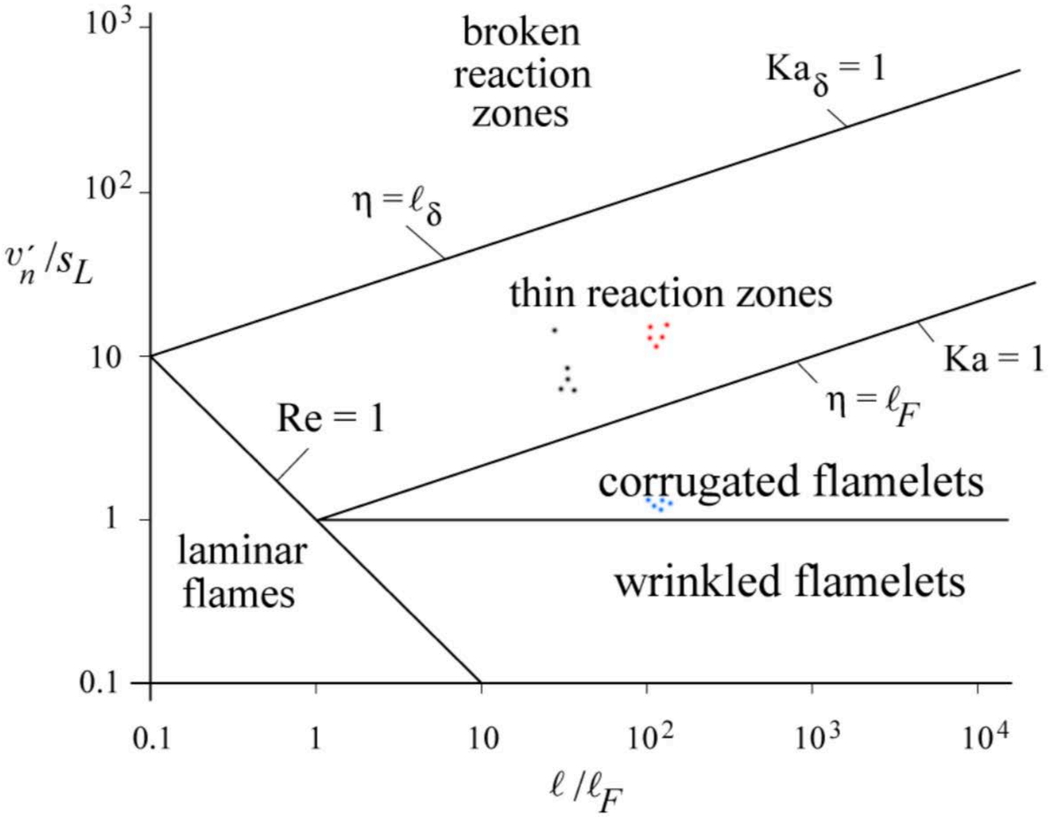

Figure 6.12: Borghi diagram with calculated points [34].

In the Borghi diagram the plotted points indicates the different configuration of the burner. The blue points give the regime for a low-swirl configuration. The black points are from a high-swirl configuration. Red points give the location in the diagram for the combined configuration where the flame settles at the exit of the burner.

The low-swirl flame is inside the corrugated flamelets area and high-swirl and the combined case is inside the thin reaction zone. This is due to an increase in turbulence and velocity. The high-swirl and combined is more turbulent cases which could be compared to the diagram. This shows that the high-swirl and combined will operate in a different combustion regime than the low-swirl flame.

6.4 Experiments done by Wärtsilä

In this heading, earlier experiments done by Wärtsilä will be presented to get a better understading of the correlation between swirl number and flame shape. Due to lack of data in experiments done in this thesis, data available from Wärtsilä would give an indication of the difference in flame shape between high-swirl and low-swirl.

From these experiments no data is provided or analyzed, only images of the flame shape and swirl number would be presented. These results are shown due to better images than was conducted at the experiments held in cooperation with this thesis and will give a better indication on how the flame shape changes by changing the swirl-number. The images do not have the same quality due to it is picked from a document [5].

The first experiment was a low-swirl case conducted with a 100-hole plate which gave the swirl-number 0.5. Blockage of 35% which is in between the ratio given in the excel sheet to achieve the low-swirl flame shape. In Figure 6.13-6.17 the burner exit is on the right side in the image, opposite to the images presented in Chapter 6.3.

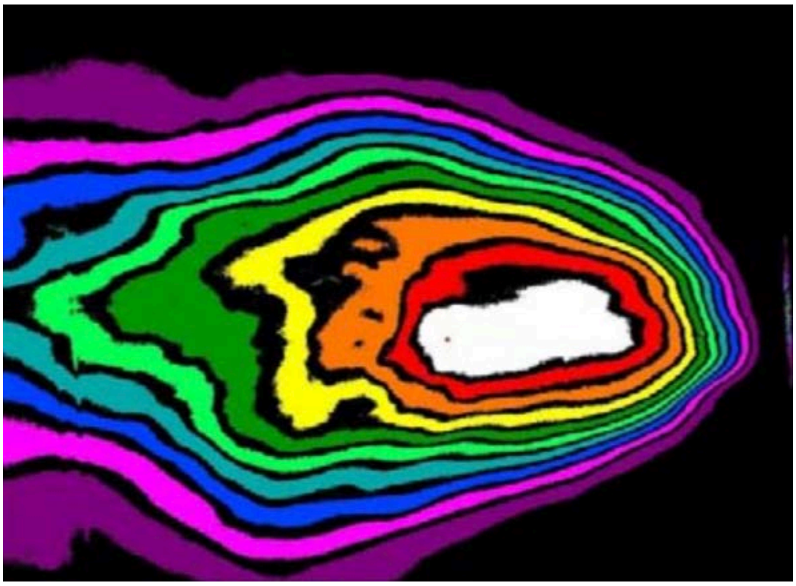

Figure 6.13: 100-hole plate [5].

The characteristic low-swirl flame shape is achieved.

The next experiment was conducted with a 110-hole plate and a swirl-number 0.45. This swirl-number is in between the range presented in the excel sheet and the low-swirl flame shape should occur. The blockage ratio was 40%. Figure 6.14 shows the flame shape in a low-swirl configuration.

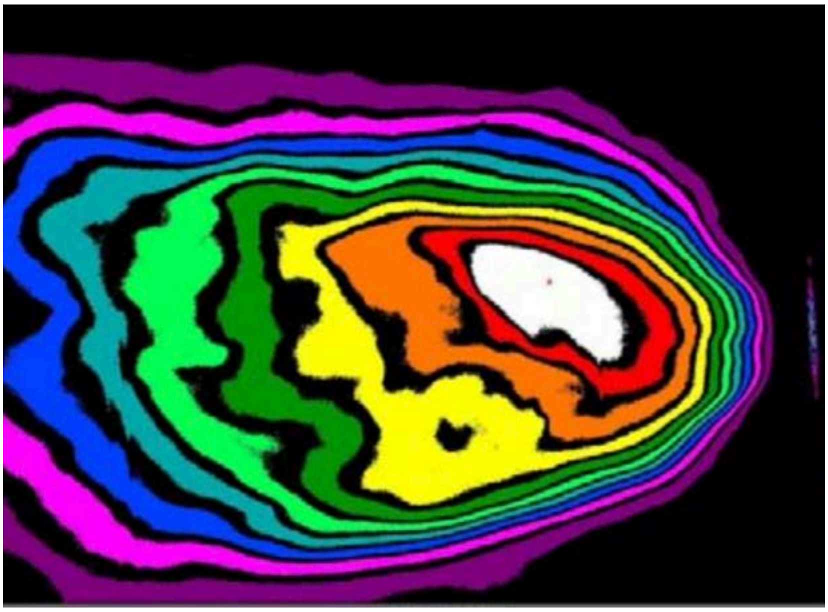

Figure 6.14: 110-hole plate [5].

This flame is lifted off the burner and has a spherical shape. A typical low-swirl flame shape is achieved.

The next experiment, and the last was conducted with a 120-hole plate. This operates with a swirl-number 0.4 and a blockage of 44%. This flame shape is shown in Figure 6.15.

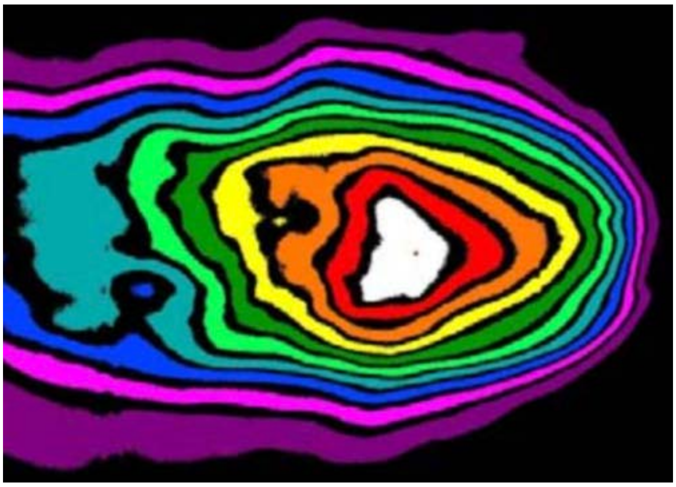

Figure 6.15: 120-hole plate [5].

The characteristic low-swirl flame shape is achieved.

The next two experiments are with a closed center channel which applies that the burner will operate as a high-swirl burner. This should give a different flame shape. The burner is operating with two different vane angles which gives two different swirl-numbers.

The first experiment operates with a vane angle of 38° and a swirl number of 0.67. The flame shape is shown in Figure 6.16.

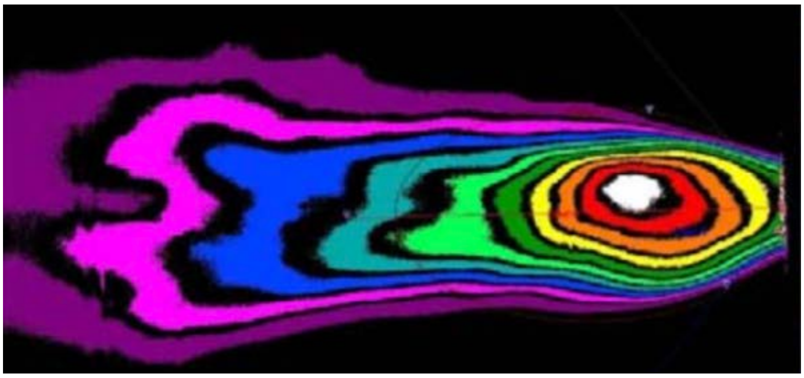

Figure 6.16: High-swirl with 38º [5].

Totally different flame shape compared to a low-swirl flame shape. This cylindrical shaped flame shape shows that for a different swirl-number the flame shape would change.

The next experiment was conducted with a vane angle of 41º. This increases the swirl-number to 0.74. Figure 6.17 presents the flame shape of the last experiment.

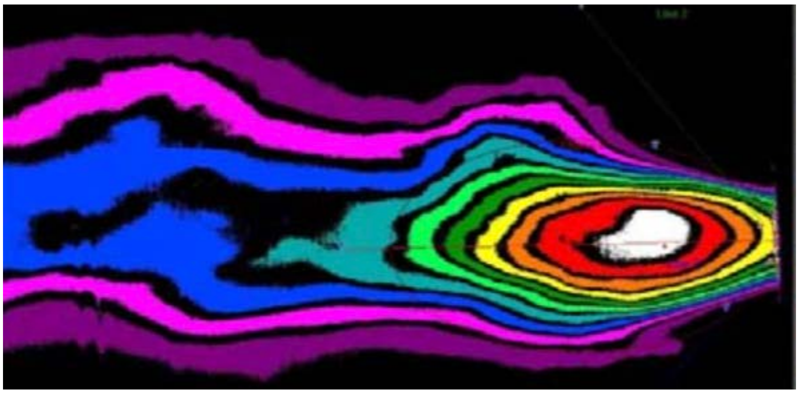

Figure 6.17: High-swirl 41º [5].

High-swirl flame shape (cylindrical) conducted with a higher swirl-number due to an increase in vane angle. In this image the outer region has more of a wave form, this could be due to an increase in vane angle which implies a stronger swirl.

This experiment conducted by Wärtsilä clarifies that there is a correlation between flame shape and swirl number. For a low-swirl burner the swirl number is between 0.4-0.5 where a characteristic low-swirl flame occurs. The flame has a spherical form. For the high-swirl burner the swirl number is between 0.67-0.74. This gave a flame shape that looks like more like a jet flame. The flame has an elongated shape and looks more like a cylinder.

7 Discussion

The discussion is divided into three parts. The first section contains a discussion around low-swirl burner as a method for handling boil-off gas compared to already existing methods. The second part discusses the topic about emissions, where it is important to turn the focus towards lowering NO_x emission from the shipping industry. The third and last part is about the results discovered in this thesis.

Three methods for handling boil-off gas are described in this thesis (Chapter 2). Reliquefaction and the scrubber system is already existing systems where both handles the problems connected to the boil-off gas. Therefore, it is unfair to say that the combined high/low-swirl system would solve all the problems connected to boil-off gas handling. However, from a theoretical point of view it is a promising method that could be a technology used to handle boil-off gas in the future. A big advantage connected to the low-swirl burner is that the system is simple, robust and readily adaptable technology. Cheng mentions that the system could be implemented without making any large changes in the system configuration which is also an advantage [4]. As Wärtsilä already offerers the scrubber system which has a comparable system configuration, it would most likely not be an issue to implement the combined system.

Emission has not been the focus of this thesis, but it is mentioned due to strict emission demands. This thesis has not presented any data on already existing system pollution and can only states if the new combined system is a promising technology in an emission point of view. In several reports [10], [4], [12] low-swirl burner has shown promising emission results when it comes to NO_x and it is in this thesis discovered that under stable conditions this emission results is possible to achieve. It is mentioned that NO_x is one of the main challenges connected to the shipping industry which is why the low-swirl burner is tested. There is none comparable data to see if the low-swirl burner achieved lower emission than existing systems but in experiments done it has shown that the experimental values is achievable. Therefore, it is a promising technology due to low emission results that has been shown through experiments.

The first experiment conducted with the high-speed camera has not been analyzed mathematically due to lack of data. This experiment showed that the combined high/low-swirl technology worked as it was intended. The input was premixed methane and air for both configurations. This would not be the case in the real system. It was not possible to do experiment for the high-swirl burner with the mixture it is intended to handle. Due to positive findings in testing of the combined high/low-swirl system, further research is encouraged. From images it was also possible to see a clear difference between the two flame shapes connected to the different swirl-numbers.

In the second experiment a high-speed camera analyze was intended. An improvement of the rig was made to shield it from weather conditions. The shielded rig was surrounded by a heat field from the heat generated from the burner. This heat field was so strong that a setup of the camera was impossible. Therefore, Wärtsilä conducted the data used for the analysis. The analysis was divided in two parts, an image part where the flame shape was investigated and an analysis part where the flame was implemented in a Borghi diagram to see if it occurred in different combustion regimes. Four of the experiments was conducted by using a quarl trying to reduce the noise and stabilize the flame. From the experiments and data available it is hard to state how it turned out. A suspicion of thermal reflection from the flame to the quarl makes it difficult. However, from the first experiment with the 360mm quarl it does not look like the lifted flame occurs. This due to an indication of attached flame. The second experiment with the 280mm quarl looks like an early phase of a lifted flame. It does not look completely lifted but has a clearly spherical shape. Third experiment was conducted with a 190mm quarl. It was in this experiment the suspicion of the thermal reflection came to mind due to two white dots (one inside the quarl and one in the flame outside the quarl) and a flame that had shape of a characteristic low-swirl flame. As stated it is hard to be 100% sure due to lack of data but it looks like a lifted flame. In the 100mm quarl experiment it looks clearly like a lifted flame occurs just outside the expansion.

From the experiment it gives an indication that a few design parameters have to be taking into account due to the change of environment in the future (combustion chamber). The area of the combustion chamber (diameter) has to be big enough to let the flame develop as a lifted flame due to the relationship between local flow velocity and turbulent flame speed. Another solution could be to build a bigger burner that reduces the bulk flow velocity since it is area dependent. Another parameter could be the stoichiometry of the flame. Due to a semi-closed chamber the environment that the flame is in changes and could be solved by inject air into the expansion.

The last experiment was conducted by Wärtsilä and is implemented in the report because of images used in evaluation of the correlation between swirl-number and flame shape. From the images it shows that the flame shape depends on the swirl-number. For the swirl-numbers from 0.4-0.5 the low-swirl flame shape occurs. The high-swirl flame shape occurred at swirl-numbers between 0.67-0.74. The last experiment was with an increased vane angle which gave a wave form in the outer region of the flame. This could be due to an increase in swirl-number which gave the flow a more swirling motion.

The change in swirl-number gives a change in flame shape from a low-swirl to a high-swirl configuration. The change in swirl-number within the range of a low-swirl configuration, does not show significant difference. This is probably due to similar flame shape and that a tool for investigate the dimensions in each flame has not been available in this thesis. Therefore, in this experiment the correlation between flame shape and swirl-number is only seen in a change of configuration. The Borghi diagram implies that there is a change in combustion regime between high- and low-swirl. The high-swirl is more turbulent case. The different combustion regimes are a good indication of the different flame shapes.

8 Conclusion

In this thesis there has been developed an algebraic method for analyzing the flame and design parameters for a combined high/low-swirl burner system for boil-off gas handling. There has been done some findings.

Under stable operating the burner achieves emission that is comparable with earlier experiment conducted. This implies that the swirl-burner could be an environment friendly technology for boil-off gas handling.

It is possible to combine high- and low-swirl configuration into one burner. The design principles are important to achieve such a burner. The parameter that adjust the burner configuration is the swirl-number. This parameter changes the burner mechanism between high-swirl and low-swirl. In this thesis experiments are conducted by different swirl-numbers. Swirl-number that is in between 0.4-0.5 makes it possible to achieve a low-swirl mechanism. A high-swirl flame is achieved by closing the center channel that raises the swirl-number between 0.67-0.74. The different flame shapes appear in different regimes in the Borghi diagram. In this analysis it is seen that the high-swirl burner creates more turbulence. When the burner changes from high-swirl to low-swirl it is discovered an increase in turbulence both in Borghi and turbulent Reynolds number.

With some improvements and further testing a low-swirl burner could be an environment friendly equipment for handling of boil-off gas.

Recommendations for future work:

- Cooling device of the combustion chamber to get control of the NO_x emission.
- Increase the diameter of the burner which reduces the bulk flow velocity to see if it makes the change between high-swirl and low-swirl easier.
- Test the high-swirl burner with the intended mixture.
- Injection of air into the combustion chamber to keep the stoichiometry of the flame intact.
- High-speed camera to get an idea of how the recirculation zone behaves for both high-swirl and low-swirl.
- Configuration of the thermal camera (or software) so that the color in the images has the same temperature scale. This would give a better understating of the temperature of the flame. Position of the camera is important to reduce the possibility of thermal reflection.
- Installation of the equipment on a vessel due to testing in the right environment.

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Appendices

Appendix A Task description

Appendix B Matlab code

University College
of Southeast Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Boil-off gas handling for LNG-carriers with a low-swirl burner.

TUC supervisor: (Main) Joachim Lundberg, PhD. (Co-supervisor) Knut Vågsæther, PhD.

External partner: Odd Ivar Lindløv, Wärtsilä Moss AS

Task background:

LNG tankers are designed to carry natural gas in liquid form at a temperature of -163°C, close to the vaporization temperature. Despite tank insulation designed to limit the admission of external heat, even a small amount of it will cause slight evaporation of the cargo. This natural evaporation, known as boil-off gas is unavoidable and has to be removed from the tanks in order to maintain the cargo tank pressure.

Wärtsilä supplies combined inert gas generators and gas combustion units for LNG Carrier vessels. The systems have a maximum volume of up to 3800 kg/h, which is sufficient for the industry's largest LNG carriers. The concept of combining the two systems was developed by Wärtsilä. The system uses an existing Wärtsilä Moss inert gas generator (see Figure 1) to burn the boil-off gas, thereby eliminating the need for a conventional gas combustion unit. This results in considerable capital expenditure savings. At the same time, by using the boil-off gas as fuel for creating inert gas, the combined system also provides notable operating cost savings.

The combined IGG-GCU system has a minimal environmental footprint. This is achieved through the replacement of a separate onboard system, and by using the boil-off gas for inert gas generation, which together minimize the extra use of marine diesel oil (MDO) fuel.

Figure 1: Inert gas generator/Boil-off gas handeling equipment

The shape of the flame is a crucial parameter to ensure a complete combustion in the IGG. The boil-off gas burner will control the shape of the flame by controlling the swirl of the flame. To find this correlation between swirl number and flame shape further research are needed.

Task description:

The target of the thesis will be to find a correlation between swirl number and flame shape. Wärtsilä Moss is in these days conducting a series of experiments with a Low-swirl burner for boil-off gas.
One suggested way of solving the task is by using high-speed imaging equipment from USN to capture images for analysis.

Student category: PT, EET. Preferably, a student with experience from experimental research, but not necessarily.

Practical arrangements:

The inert gas generator will be provided by Wärtsilä and the measurement equipment is stationed at USN.

Signatures:

Student (date and signature): 29/1-2018

Supervisor (date and signature): 29/1-2018

```matlab
clear all
clc
close all

%Number of images

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    Filename=['F:\2018Wartsila\18_SMe_P100_T0026_C001H001S0001'];


res=[1024 1024];
% % % B=zeros(1024,1024,3);
for i=1:200;
liste=dir([Filename '\*.raww']); % Listing. raww files
file1 = liste(i).name;
fid = fopen([Filename '\' file1], 'r'); %open file
x = fread(fid, [res(2)* res(1)*3], '*uint16'); % Read binary data to double % Close file
fclose ('all');
handles.numim=size(liste,1);

%Scale factor
sc=[3 1 2];

  i

    % Extracting the RGB values, storing them in each plane.
    ro = reshape(x(1:3:end-2),res)'; % Red channel
    go = reshape(x(2:3:end-1),res)'; % Green channel
    bo = reshape(x(3:3:end),res)'; % Blue channel

    red = reshape(x(1:3:end-2),res)'.*sc(1); % Red channel
    green = reshape(x(2:3:end-1),res)'.*sc(2); % Green channel
    blue = reshape(x(3:3:end),res)'.*sc(3); % Blue channel
    a = zeros(size(ro, 1), size(ro, 2));
    just_red = cat(3, red, a, a);
    just_green = cat(3, a, green, a);
    just_blue = cat(3, a, a, blue);

img = cat(3, ro, go, bo);
%     figure(2), imshow(img), title('Original image')
%     figure(3),subplot(1,3,1); imshow(just_red), title('Red channel')
%     figure(3),subplot(1,3,2); imshow(just_green), title('Green channel')
%     figure(3),subplot(1,3,3); imshow(just_blue), title('Blue channel')
    imgsc = cat(3, red, green, blue);
  figure(1), imshow(imgsc), title('Original image (Scaled)')

% % %   Br=uint16(double(red)-B(:,:,1));
% % %   Bg=uint16(double(green)-B(:,:,2));
% % %   Bb=uint16(double(blue)-B(:,:,3));
% % %   imgsub = cat(3, Br, Bg, Bb);
% % %    figure(2), imshow(imgsub), title('Original image (Scaled)')
pause(1);
% %   B(:,:,1)=double(red);
```

```
% %   B(:,:,2)=double(green);
% %   B(:,:,3)=double(blue);
end
% %
% % % % % % % %     ro(find(ro<20))=0;
% % % % % % % %     go(find(go<20))=0;
% % % % % % % %     go(find(bo<20))=0;
% % T=100./(log(double(green)./double(red)));
% % % % % % % K=(double(3.*blue)>double(blue+red+green));
% % T(find(isinf(T)))=0;
% % T(find(isnan(T)))=0;
% % % % % % %
% % % % % % %
% % % % % % % % % % figure(2), imshow((T))
% % % % % % % % % level = graythresh(T);
% % % % % % % % % %level=0.02;
% % % % % % % % % E=edge(T,'Roberts');
% % % % % % % % % BW = im2bw(T,level);
% % % % % % % % % BW=imfill(BW,'holes');
% % % % % % % % %  figure(1),
% % % % % % % % %  hold on
% % % % % % % % %  contour(BW)
% % % % % % % % %  hold off
% % figure(2), imshow(uint8(T))
% % % % % % % H=rgb2hsv(back_to_original_img);
% % % % % % % [F] = TotalVariationFilter(go,100,0.2,0.7,0);
% % % % % % %  lo=100.*log(double(go./bo));
% % % % % % % figure(3),
% % % % % % %  plot(ro(640,:),'r'), title('horisontal')
% % % % % % %  hold on
% % % % % % %  plot(go(640,:),'g')
% % % % % % %  plot(bo(640,:),'b')
% % % % % % %  plot(100.*H(640,:,1),'black')
% % % % % % %  hold off
% % % % % % % %  ginput(1);
% % % % % % % figure(4),
% % % % % % %  plot(ro(:,130),'r'), title('vertikal')
% % % % % % %  hold on
% % % % % % %  plot(go(:,130),'g')
% % % % % % %  plot(bo(:,130),'b')
% % % % % % %  plot(10.*abs(gradient(double(H(:,130)))),'black')
% % % % % % %  hold off
% % pause(1)
% %
% % end
```