INSTITUTIONEN FÖR VÄRME- OCH KRAFTTEKNIK
FÖRBRÄNNINGSMOTORER
LUNDS TEKNISKA HÖGSKOLA

Scavenging Processes in High Speed Two-Stroke Engines Studied with Laser Diagnostics

by

Martin Ekenberg

Thesis for degree of Licentiate of Engineering

ISRN LUTMDN/TMVK—98/7028--SE

DIVISION OF COMBUSTION ENGINES
DEPARTMENT OF HEAT AND POWER ENGINEERING
LUND INSTITUTE OF TECHNOLOGY
P.O. BOX 118, S-221 00 LUND
SWEDEN

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List of papers

This list contains the papers I have authored or co-authored, with comments on my part in the work. The listed papers are included in this thesis.

1. **Ekenberg, M. Johansson, B. "Scavenging Flow Velocity in Small Two-Strokes at High Engine Speed", SAE Paper 951789.** I did the major part of the measurements and evaluation. Dr Johansson made the laboratory set-up. I presented the paper at the "Small Engine Technology Conference" in Milwaukee, USA.
2. **Ekenberg, Johansson, B. "The Effect of Transfer Port Geometry on Scavenge Flow Velocities at High Engine Speed", SAE paper 960366.** I did the major part of the measurements and evaluation and presented the paper at the SAE Meeting in Detroit, USA 1996.
3. **Ekenberg, M, Johansson, B. "In-Cylinder Flow in High Speed Two-Stroke Engines with Different Transfer Channels", SAE paper 970357.** I did the major part of the measurements and evaluation and I also constructed the optical access engine. I presented the paper at the SAE Meeting in Detroit, USA 1997.
4. **Ekenberg, M, Johansson, B. "Laser Sheet Droplet Concentration Measurements in a High Speed Two-Stroke Engine", SAE Paper 972123.** I did all the measurements and the major part of the evaluation. I presented the paper at the "Small Engine Technology Conference" in Yokohama, Japan in 1997.
5. **Andersson, Ö, Juhlin, G, Ekenberg, M, Johansson, B, Aldén, M. "Crank Angle Resolved HC-Detection Using LIF in the Exhausts of Small Two-Stroke Engines Running at High Engine Speed", SAE Paper 961927.** I took part in the LIF measurements, but Andersson and Juhlin made the major part of the LIF measurements and evaluations. The LDV measurements presented in that paper were performed and evaluated by me. The paper was presented by Öivind Andersson at the "Fuels and Lubricants" meeting in San Antonio, USA in 1996.

Summary

The major problem with the carburetted two-stroke engine is the short-circuiting of fuel that occurs during the scavenging phase. This leads to large emissions of unburned hydrocarbons.

The object of this thesis has been to map the flow behaviour in the cylinder during the scavenging phase, and to detect differences between different cylinder designs. The measurement techniques used has been Laser Doppler Velocimetry (LDV), Laser Induced Fluorescence (LIF) and Laser Sheet Droplet Illumination (LSDI). Of these measurement methods, LDV and LSDI has been used inside the cylinder. LIF was used outside the exhaust port.

All measurements were performed in engines running at their rated speeds, 9000 rpm for three of the designs and 5800 rpm for one design. All engines were run at full load with combustion.

The LDV measurements inside the cylinder show that cylinders with cup handle transfer channels have a flow pattern inside the cylinder that gives less short-circuiting, and hence less emissions of hydrocarbons, than the cylinder with open transfer channels has.

The LIF measurements outside the exhaust port show that the HC emissions that are caused by short-circuiting comes earlier in the scavenging phase for the cylinder with open transfer channels than is the case for the cylinders with cup handle transfer channels.

The LSDI measurements in the cylinder give the transfer channel flow angle, for the cylinders with cup handle transfer channels. For the cylinder with open transfer channels, the results are not as useful; fuel droplet vaporisation close to the exhaust port ruins the results.

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1 Introduction

The two-stroke engine is the most uncomplicated reciprocating engine, which makes it the most common choice of engine where a high power output at a minimum price is wanted, and other aspects, as for instance fuel economy, are not that highly regarded.

The major problem with the two-stroke engine is the short-circuiting, or leakage, of fuel that occurs during the scavenging of the cylinder, since the exhaust port is open during the entire gas exchange process. The amount of short-circuited fresh mixture can be significantly reduced by using the right type of transfer channels (the channels through which the fresh mixture is entering the cylinder), actually the amount varies from about 30 percent with a simple transfer channel design to about 15 percent with a more advanced design. In this thesis, laser based methods to measure the scavenging flow behaviour inside the cylinder and outside the exhaust port are presented, along with some results that gives an explanation to the performance of some transfer channels.

The presentation is organised as follows:

Chapter 1 contains the background to this work. Chapter 2 gives a short historic overview on the two-stroke engine. In chapter 3, the engines are described, and the different techniques to make them optically accessible are presented. Chapter 4 describes the used measurement techniques, and in chapter 5, some results are presented. Chapter 6 is a discussion chapter, where the author tries to estimate some of the errors that are coupled to each measurement technique, and compare results obtained with different measurement approaches. Chapter 7 is a short summary on the work.

1.1 Background

Early in 1995, Lund Institute of Technology got in contact with two Swedish manufacturers of small two-stroke engines, Husqvarna and Atlas Copco Berema. An agreement was made, that Lund Institute of Technology (LTH) should do measurements on scavenging of two-stroke engines. A project was formed. The Swedish National Board for Industrial and Technical Development (NUTEK) and the industrial partners were cosponsoring. The project has been conducted during 1995, 1996 and the first half of 1997, within the NUTEK competence centre in combustion processes.

1.2 Acknowledgements

This project has been sponsored by Husqvarna and Atlas Copco Berema together with the Swedish National Board of Technical Development. I am very thankful to them for making this work possible.

I would also like to thank all the personnel at Combustion Engines, and in particular Dr:s Gunnar Lundholm and Bengt Johansson for their nice and competent supervision. I would also like to thank Bertil Andersson for his good humour and his almost magic ability to understand my sometimes quite dizzy ideas on how to make things work and as well make them work. Without his help, the experimental work performed would have been much more time consuming, more boring and the results would not have been so good.

The contact persons from the industries involved in the project, Bo Andreasson, Bo Jonsson, Hans Ström and Roy Ekdahl from Husqvarna AB, Per Fridolfsson, Stefan Jacobsson and Peter Karlsson from Atlas Copco Berema have also been of great help, and deserve a large portion of gratitude.

I would also like to thank Greger Juhlin, Öivind Andersson and Marcus Aldén from the Division of Combustion Physics for their help with the LIF measurements performed.

My room-mates Patrik Einewall, Fredrik Söderberg and Magnus Pålsson at the Division of Combustion Engines have not only been good friends, but as well served as excellent discussion partners.

Finally, I would like to thank my girlfriend Maria Rosén for her support and understanding, and for giving birth to our lovely daughter Kajsa.

2 Two-stroke engine fundamentals

The two-stroke engine is not only known for its willingness to run at high RPM:s, its high power to weight ratio and simple design, but is infamous for having high emissions of unburned hydrocarbons and hence bad efficiency.

2.1 Basic working principle

The two-stoke engine is the most mechanically uncomplicated engine design. It works with two different strokes only: One compression stroke and one expansion stroke. The gas exchange takes place as the piston is close to the bottom dead centre, where the exhaust gases leaves the cylinder at the same time as the fresh gas enters it. In figure 1, the basic working principle of the two-stroke engine is shown.

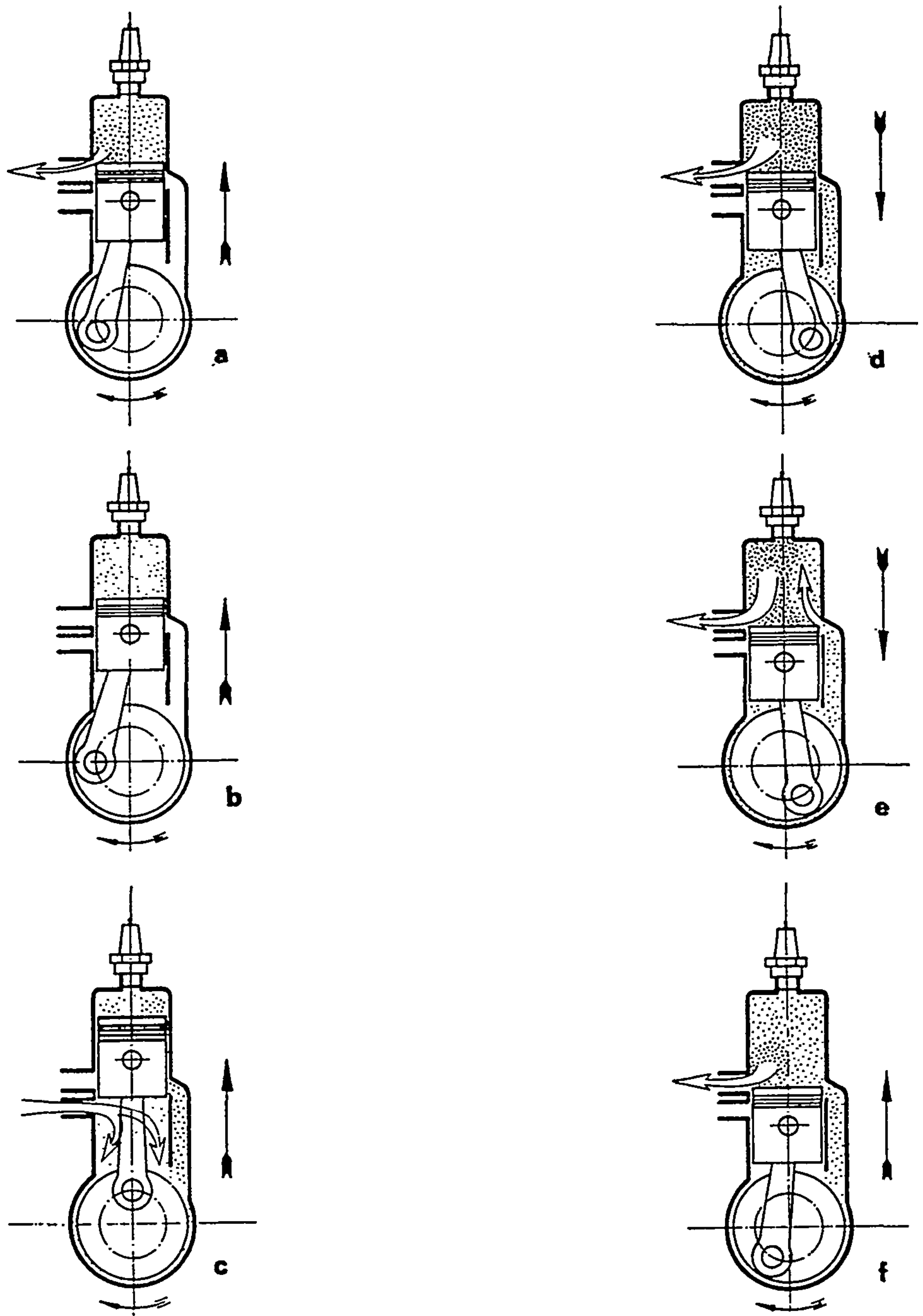

Figure 1 The working principle of a two-stroke engine with crankcase compression[7].

a. Above the piston, the exhaust port is just about to close. Below, the raising piston depresses the content in the sealed crankcase.

b. Above the piston, the compression of the charge has begun, and in the crankcase the pressure drop continues.

c. The inlet port has opened and the crankcase is filled with fresh gas.

d. The expansion phase is over and the exhaust port has opened to let the exhaust gases out (blow-down). The pressure in the crankcase has increased due to the closing of the inlet port and the pistons down-going motion.

e. The transfer ports open to let the cylinder be scavenged by the fresh gases. The pressure in the crankcase decreases rapidly.

f. The process is about to start all over again.

2.2 History

The two-stroke engine was invented as a way to circumvent Nikolaus Otto's patent on the four-stroke engine. The literature argues about who really was the inventor, but usually sir Dugald Clerk gets the credit, maybe because England did not have a "cycle inventor" as Germany had Otto and France had Beau de Rochas.

2.2.1 Clerk

Sir Dugald Clerk (1854-1932) devoted at least ten years of his career to the development of two-stroke engines without having any big success with his own designs. His patent on the two-stroke engine originating from 1878 and presented to the public in 1879 worked on the principle that one cylinder performed the intake and compression of the scavenging air and one main cylinder that further compressed the mixture and after ignition performed the work stroke. In figure 2, Clerks two-stroke engine from 1883 is shown. This engine produced about 0.5 horsepower at 210 revolutions per minute. Note the two cylinders, one for supplying compressed scavenging air (at right) and one for producing work (in the center)

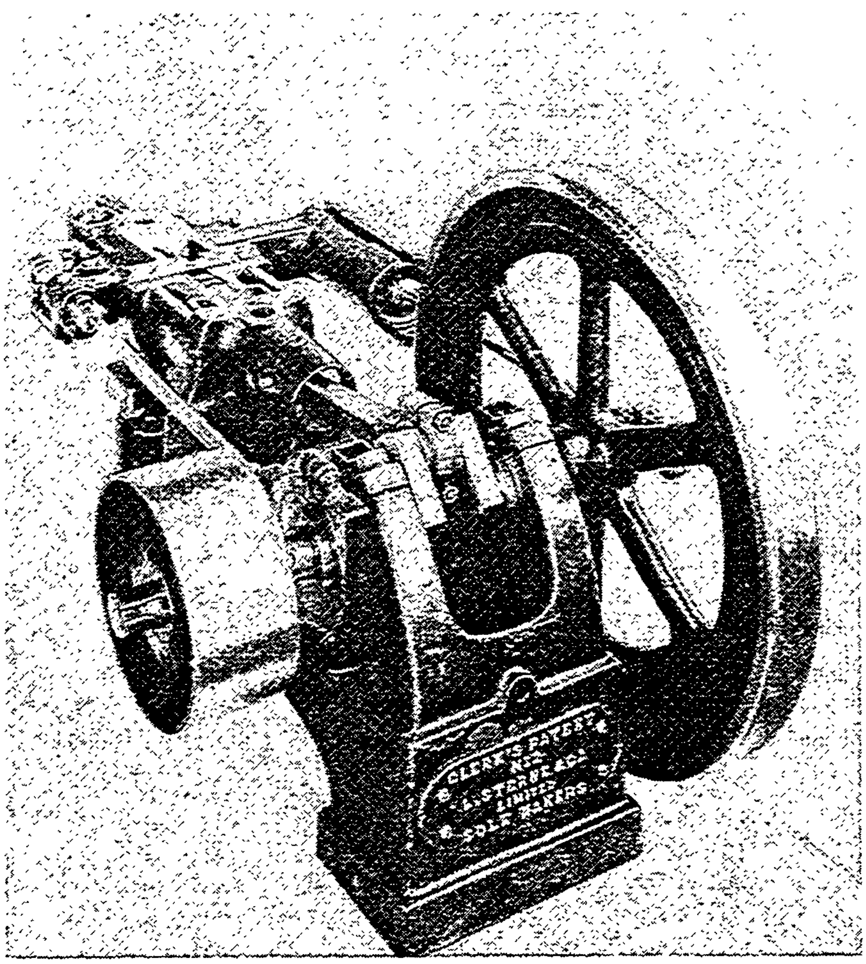

Figure 2 Sir Dugald Clerks two-stroke engine from 1883.[8]

2.2.2 Day

Joseph Day's (1855-1946) contribution to the two-stroke engine technology was the "three-port" design, i.e. the use of the piston to control all the valves necessary to run a two-stroke engine and the use of the crankcase to supply the scavenging air. In Day's engine, three different valves are used; The valve to let the scavenging air into the sealed crankcase, the transfer port to let the scavenging air into the cylinder, and the exhaust port to let the exhaust gases out from the cylinder. Day's design is the most common for small engines to this day, especially for the smallest engines, used in small mopeds and in hand-held tools, such as the ones produced by Husqvarna and Berema.

For larger two-stroke engines with higher requirements on power and low speed torque, the most common way to control the flow into the crankcase is to use a one-way valve (reed valve). Actually, one of the engines was equipped with this type of inlet valve, but a more typical choice for small engine is the piston controlled inlet valve as proposed by Day.

Day's engine had most benefits two-stroke engines have to this day; it was uncomplicated and had few moving parts (compared to Dugald Clerks engine).

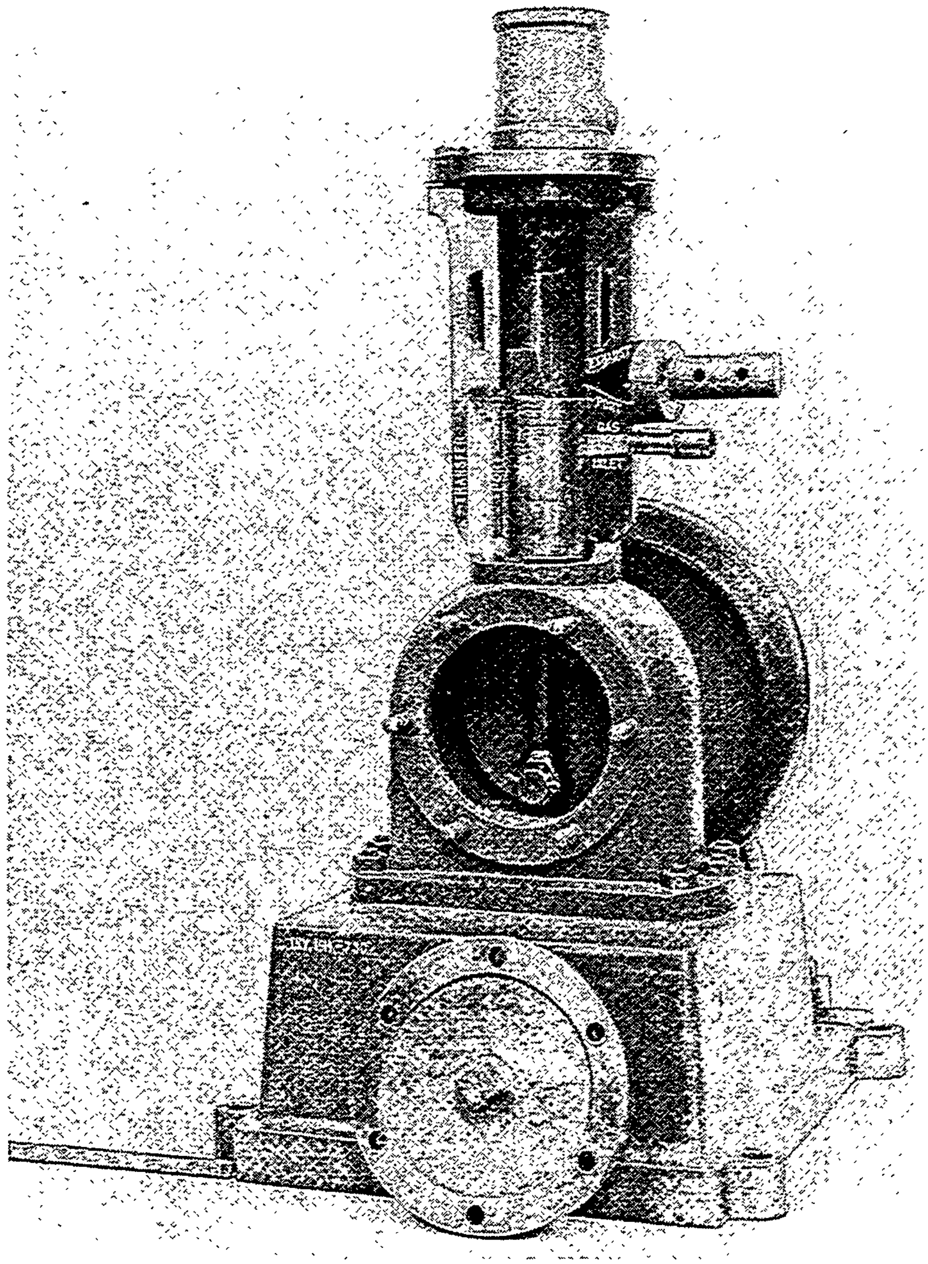

***Figure 3** Joseph Day's "Three-port" design 1892. All necessary valves (ports) are controlled by the piston position. Note as well the deflector on the piston. It is supposed to induce a "loop" in the scavenging flow, and thereby reduce the short-circuiting.[8]*

2.2.3 Scavenging principles

In this chapter, three types of scavenging principles will be described; Cross scavenging, loop scavenging and uniflow scavenging.

As mentioned in the introduction, the main problems with the two-stroke engine is that it short-circuits a part of the fresh fuel/air load and that the cylinder content is not pure fresh gas. This phenomenon, known as short-circuiting, means that a part of the fresh load that enters the cylinder through the transfer ports flows out through the exhaust port during the gas exchange without taking part in the combustion. This of course leads to a bad fuel economy and high amounts of unburned hydrocarbons.

After the "blow-down" phase, the time period during which the pressure in the cylinder decreases rapidly due to the opening of the exhaust port, the absolute pressure in the cylinder is about 1 bar (atmospheric pressure). As the scavenging goes on, the pressure in the cylinder stays at about 1 bar, and some of the exhaust gases are replaced with fresh mixture. The torque delivered by the engine can therefor be approximated almost linearly to the purity of the fresh gas in the cylinder. This leads to a very diluted fresh gas in the cylinder at part load (the dilutant is burned gases that has not left the cylinder). In a diluted air-fuel mixture, the flame velocity decreases. This is the reason why two-stroke engines are infamous for their poor low load characteristics (large cycle-to cycle variations and misfire lead to uneven run and "four stroking").

The combustion stability can be increased if the fresh fuel and air mixture is "globally" diluted, but is less diluted near the spark plug (known as stratified charge).

The main features wanted from a good scavenging is therefor: Low amount of short-circuited fuel at all loads, and hence low HC emissions, and good capability to run the engine at low load (by stratifying the charge).

2.2.3.1 Cross scavenging

The first scavenging model used was what today is called the cross scavenging. In a cross-scavenged cylinder, the exhaust port and the single transfer channel are placed on opposite sides of the cylinder. This would, if the piston was flat lead to a huge amount of short-circuited fresh gas mixture. However, in cross-scavenged engines the piston is not flat, but has a deflector that is supposed to direct the flow from the transfer port up towards the cylinder head.

Cross scavenging is a common choice for multi cylinder outboard marine engines, since a cross scavenged design offers packaging advantages over the loop scavenged designs, due to the placement of the transfer channels. On loop scavenged engines, the transfer channels are placed on the sides of the cylinder. This means that for in-line multi cylinder engines, the distance between the cylinders must be substantially larger than for a cross scavenged design. In figure 4, a typical cross scavenged design is shown.

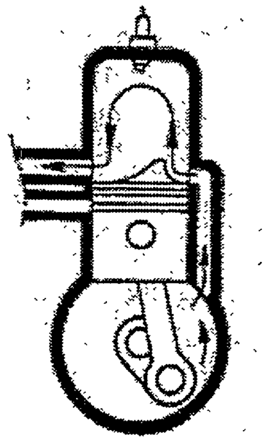

Figure 4 Typical design of a Cross-scavenged engine. Note the deflector on the pistontop.[31]

In short-circuiting terms, a good cross-scavenged engine is about as good as a good loop-scavenged design.

One disadvantage with the cross-scavenged engine is the deflector in the top of the piston. The deflector is not only expensive to manufacture, it also makes it hard to design a good combustion chamber. Furthermore, the piston temperature increases slightly, due to the larger area of the piston.

2.2.3.2 Loop scavenging

The loop scavenging was invented by German Schnürle in 1926, and is the most common scavenging type on small, high performance engines, such as chain saws, brush cutters, motorcycles etc. Schnürles main reason for proposing the loop scavenging was the hot running characteristics of the deflector on the piston top in the cross-scavenged engines.

The basic principle of the loop-scavenging can be seen in figure 5. The procedure can be described as follows:

- The transfer ports, that are placed on the sides of the cylinder, are directed towards the "back" wall of the cylinder, i.e. opposite the exhaust port.
- At the back wall, the two flows from the transfer ports meet and a motion upwards results.
- As the up-going flow reaches the cylinder head, it turns downwards and flows towards the exhaust port. This up an downward motion is the reason for the name "loop"
- Just as the flow of fresh mixture reaches the exhaust port, the port is supposed to close to trap the fresh mixture in the cylinder to minimise the short-circuit losses.

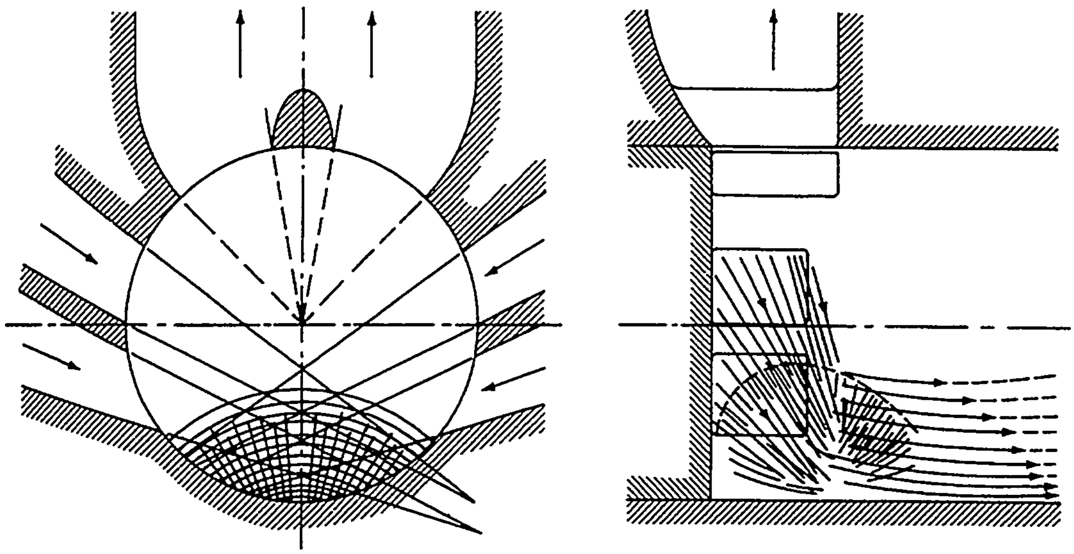

Figure 5 Desired flow in a loop-scavenged engine.[22]

However, many problems might come up:

- The horizontal angle of the transfer channels might be too steep, i.e. too much directed towards the back wall. The flow will then not turn upwards at the back wall, but instead stay in the horizontal plane and be directed more towards the exhaust port. This leads to a high amount of short-circuited fresh mixture.
- The vertical angle might be too small or large. If the flow is very parallel to the piston top, the same thing might happen as when the flow is directed too much towards the back wall. On the other hand, if the flow is directed too much upwards, the cooling effect on the piston that is supported by the incoming fresh mixture will decrease, and engine seizure may be the result.
- The timing might not be perfect: The exhaust port may not close when the fresh mixture arrives. If the exhaust port closes too late, a large amount of fresh mixture will be lost through the exhaust port. On the other hand, if it closes too early, less exhaust gases will leave the cylinder and the output of the engine will decrease.

2.2.3.3 Uniflow scavenging

The uniflow scavenging is the best scavenging principle known, but unfortunately, the complexity of the design makes it too heavy and expensive for use in small engines. The uniflow scavenging is used in large engines, i.e. large marine diesels and power plants ashore, and in few medium large two-stroke diesel engines. The Detroit diesel engine is one example of these engines (shown in figure 6)

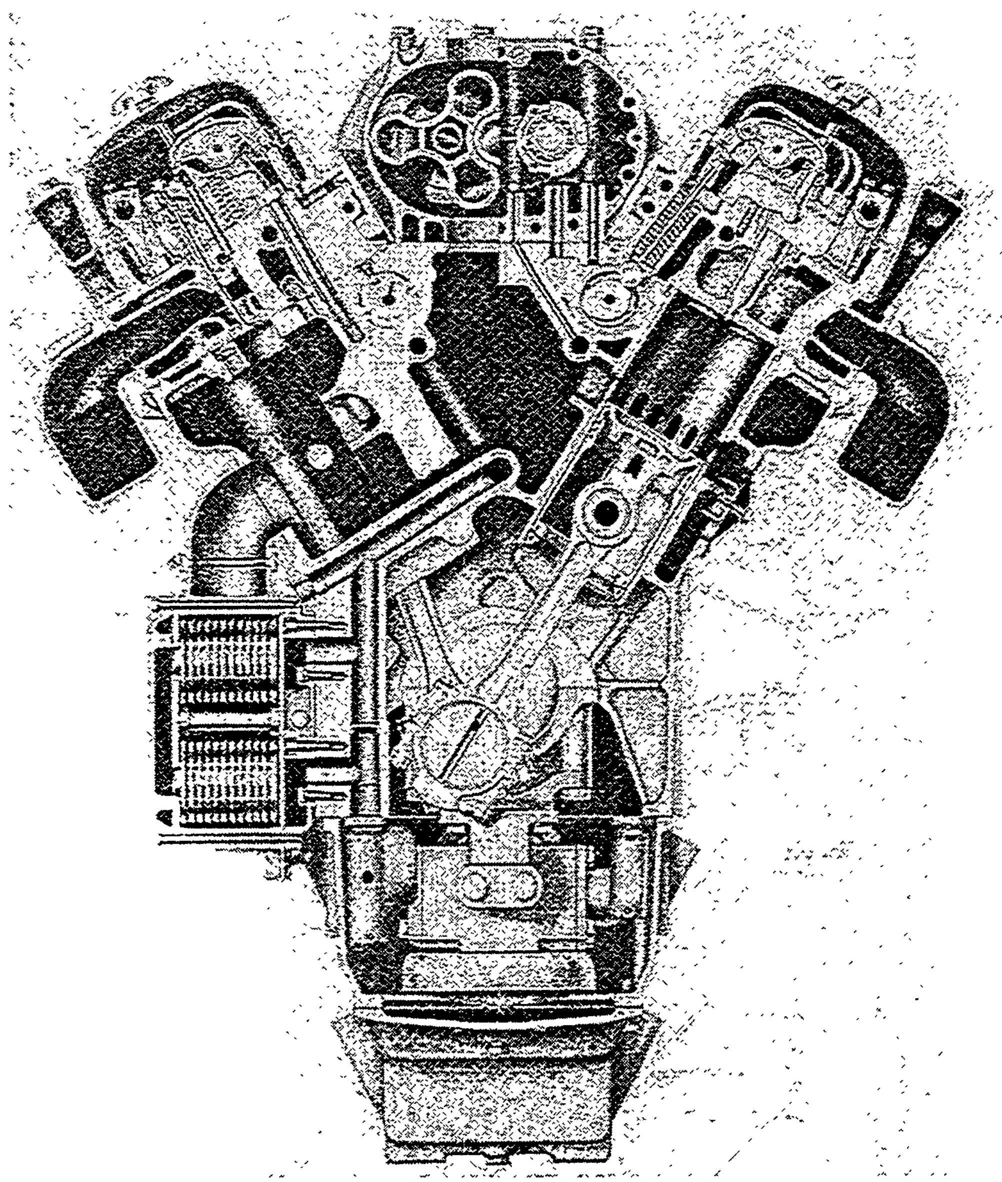

Figure 6 General Motors Detroit Diesel series 71 V Engine. The picture shows a typical Uniflow scavenging system with exhaust valves in the top of the cylinder. The engine is used in community buses in the US [32].

The uniflow scavenging uses valves in the top of the cylinder to let the exhaust gases out from the cylinder, and scavenging ports in the bottom of the cylinder supplies the fresh air. The opposite configuration, with the exhaust ports in the bottom of the cylinder and the inlet ports in the top is also used [4].

The large two-stroke diesel engines usually have a stroke/bore ratio exceeding 2, which makes the uniflow scavenging particularly beneficial in these engines (a scavenging becomes more efficient if the flow goes through a long narrow "pipe", since the mixing with the exhaust gases then is reduced).High speed engines have stroke/bore ratios from 0.9 to 1.3 and on those, a good loop-scavenging is almost as good as the uniflow scavenging [4].

The inlet ports, or valves (that, as mentioned, can be placed in the top or the bottom of the cylinder), are usually configured so that the scavenging air gets a swirling motion. This does not only improve the combustion, as in four-stroke engines, but also improves the scavenging efficiency.

Principally, there is nothing that excludes the use of the crankcase as supplier of scavenging air for uniflow engines, but it is more common to use some kind of external blower that is driven either by the crankshaft or the exhaust gases (turbo charging).

2.3 Two-stroke characteristics

2.3.1 Simplicity/production cost

The two-stroke engine is very simple, since it only consists of three moving parts; the piston, the connecting rod and the crankshaft. The four-stroke engine has a lot more moving parts: at least two valves in the cylinder head, one camshaft and one oil pump to ensure proper lubrication of all engine parts. On small two-stroke engines, the lubricating oil is added to the fuel. In the UK, this way of lubrication is called petroil.

If crankcase compression is used for scavenging air, the crankcase must be sealed. This adds to the two-stroke engine's complexity, but is a minor one compared to the total complexity of the four-stroke engine [9].

To save production cost, it is today common practice to cast the cylinder, cylinder head and "upper" half of the crankcase in one piece, and hence reduce the total number of engine elements to: Cylinder, piston (with rings), connecting rod, crank shaft and the lower part of the crankcase. Another advantage with this design is that the lower part of the crankcase can be made from plastic instead of casted metal, since the heat from the cylinder does not reach the lower part of the crankcase that is cooled by the scavenging air.

2.3.2 Power to weight ratio

The two-stroke engines high power to weight ratio comes from the twice as many work strokes per revolution compared to that of the four-stroke engine, its lower weight due to incomplexity of the engine and the ability to run at high engine speeds.

The specific output can be further increased by the use of a "tuned" exhaust pipe. Tuned two-stroke engines can reach output powers exceeding 400 hp/litre swept volume. The price that has to be paid for the high specific output in a tuned engine is the rather uneven torque curve: a tuned two-stroke engine delivers its maximum torque in a very narrow speed range, reducing the driveability substantially.Tuned exhaust pipes are most common on motorcycles, where a high output power is a good argument for sales, and the reduced rpm area for maximum torque can be used more frequently by using a larger number of gears.

2.3.3 Fuel consumption

The fuel consumption of small, carburetted two-stroke engines is higher than for equivalent four-strokes, mainly for two reasons; the fuel lost through short-circuiting mainly at high loads and the poor combustion stability at low loads due to the dilution of the fresh gases. Furthermore, many two-stroke engines run at fuel mixtures substantially richer than stoichiometric, in order to reduce the temperature of the piston and cylinder. This is however no "inherent" reason for high fuel consumption, and can be reduced by adjusting the carburettor to a leaner mixture. This is, however, at the expense of reduced engine life and higher risk of engine seizure.

The fuel consumption can be significantly reduced by using an injection system that injects the fuel directly in the cylinder. The cylinder is then scavenged with air only, and thereby the short-circuiting losses of fuel are extinguished. The combustion quality at low loads is as well significantly improved due to the charge stratification possible with such a system (charge stratification means that the fuel is concentrated in the vicinity of the spark plug and gives a better flame propagation and more stable combustion than is the case with a homogenous mixture).

Unfortunately, the injection systems are still too complicated and expensive to be a realistic alternative to the carburettor, at least for small engines. On larger two-stroke engines (powers exceeding 50 hp) the direct injection systems are in production, and has proved to be a great improvement in terms of improving the fuel consumption and reducing the emissions [1, 27, 29].

2.3.4 Emissions

Legislations have limited the allowed emissions from internal combustion engines in general during the last decades. The legislators have concentrated on four different emissions; unburned hydrocarbons, carbon monoxide, particulate and nitric oxides. The emission of CO_2, carbon dioxide, are not yet regulated. The only possible ways to reduce the emissions of CO_2 are either to reduce the fuel consumption or to run the engines on fuel that contain less carbon.

2.3.4.1 Unburned Hydrocarbons, HC

For two-stroke engines, a major emission source for hydrocarbons is the short-circuiting of fuel that occurs since the exhaust port is open during the scavenging of the cylinder [18]. The other phenomenon is the dilution of the fresh mixture that occurs due to the high amount of residual gas in the cylinder. As mentioned earlier, the dilution causes unstable combustion and some cycles do not ignite at all. Needless to say, cycles that do not burn at all produce large amounts of unburned hydrocarbons.

The lubrication in small two-stroke engines is of the "total loss"-type, which means that all oil that lubricates the engine is lost through the exhaust port. This oil adds on to the total emissions of hydrocarbons, but the oil part of the total HC emission is not larger than 10-15 % [24].

Four-stroke engines generally emits much less hydrocarbons than two-stroke engines do. The major HC emission source for this type of engine is the volume between the piston and the cylinder, over the top piston ring. This crevice volume is too narrow to allow a flame to propagate there, but large enough to host up to eight percent of the fresh mixture [17]. Of course, this emission source is as well present on two-stroke engines, but is still small compared to the other emission sources.

2.3.4.1.1 Toxicity

The two-stroke engine is widely spread for use in applications where the engine works quite near the user of the engine, and the use of two-stroke engines is common in environmentally sensitive areas such as lakes (outboard motors) and city areas (brush-cutters, grass trimmers etc).This means that not only the amount of emitted hydrocarbons, but also the toxicity of them are of great interest.

The use of petroleum based fuels have changed the last decades, from a large consumption of heavy hydrocarbons for use in district heating and power production towards a larger consumption of lighter hydrocarbons such as gasoline for cars and kerosene for jet engines. The crude oil is a mixture of different hydrocarbons with different boiling points, and before about 1970, each crude oil fraction was sufficient to fill the need for each specific hydrocarbon demand.

As the consumption turned towards lighter hydrocarbons, the refineries could not just destill the crude oil to separate the different fractions, but started to crack the large hydrocarbons to smaller ones. This led to a deterioration of the fuel in environmental terms, since cracked hydrocarbons are unsaturated and therefor more reactive.This deterioration is more severe for the use of two-stroke engines than it is for four-stroke engines, because of the higher emissions of unburned hydrocarbons.

2.3.4.1.1.1 Alkylate fuel

In the late 80:s, a fuel with less toxicity than ordinary gasoline was introduced in Sweden [33]. The main content in this fuel is so called alkylates, which means that the hydrocarbons are saturated and hence less reactive and therefor less toxic.

In Sweden, the alkylate fuel is sold at gas stations, at a price substantially higher than the price of ordinary gasoline, mostly due to the small sales volumes and the necessity to sell it in separate bottles.

2.3.4.2 Carbon Monoxide, CO

Carbon monoxide, CO, originates from burning of fuel under richer than stoichiometric conditions, i.e. the oxygen content in the air is not sufficient to completely oxidise the fuel to water and carbon dioxide only [17].

The reason to run a two-stroke engine under such fuel-rich conditions is problems with overheating of the cylinder and piston top. If extra fuel is added, the combustion temperature decreases and hence the temperature of the piston top and cylinder are reduced. The same effect can be obtained at leaner than stoichiometric conditions, but if the mixture is leaned out, the combustion quality gets worse, and the combustion quality in the two-stroke engine is poor enough already at rich conditions.

Modern four-stroke gasoline engines in cars mainly runs at stoichiometric condition, since three-way catalysts only work at stoichiometric condition. However, on full load most four-stroke engines run at fuel-rich mixture, causing substantial CO-emissions.

2.3.4.3 Particulate

Particulates usually do not constitute a problem for Spark Ignition (SI) engines, but for two-stroke engines with the lubricating oil added to the gasoline, particulates can constitute a problem. This problem has been reduced the latest years by the use of so called "low smoke" oil.

2.3.4.4 Nitric Oxides, NO_X

NO_X is formed by the nitrogen and the oxygen in the air under high temperature. Two-stroke engines usually emit low amounts of nitric oxides, due to the dilution of the burning mixture with exhaust gases and hence lower flame temperature.

The fuel rich mixture used in the two-stroke engine as well reduces the emission of nitric oxides, due to both the lower combustion temperature that results in a rich mixture and the lack of oxygen needed to form NO_X.

2.3.4.5 Catalyst capabilities

Four-stroke engines for use in automotive applications are in Europe and in the US equipped with so called three way catalysts. Such an arrangement reduces the emissions of the legislated emissions (HC, CO and NO_X) to very low levels if the engine runs under stoichiometric conditions. The control system to keep the engine under stoichiometric condition is sophisticated, and even small diversions from the stoichiometric conditions severely reduce the tree-way catalytic conversion . Slightly fuel rich mixtures give excellent NO_X conversion but poor conversion of HC and CO. Slightly lean conditions give excellent conversions of HC and CO, but no NO_X conversion at all. The problem with the non-existent NO_X conversion at lean running conditions is even more emphasised as the engine out emissions of NO_X peaks under slightly lean conditions.

Three-way catalysts on small two-stroke is not economically possible, since the price of an entire small two-stroke engine often is lower than just one component in the automotive three-way catalyst system.

On the other hand, the nitric oxide emissions from the two-stroke engine are low, and hence not very important to reduce further. What is needed on the two-stroke engine is therefor an oxidising catalyst, that reduces the emissions of HC and CO. To reduce CO and HC, oxygen is needed, and oxygen is present in the exhausts, since the short-circuited mixture contains oxygen.

An oxidising catalyst is therefor suitable for use in two-stroke applications. There is however one severe problem with the addition of an oxidising catalyst to the two-stroke engine; the heat.

Since a large amount of the fresh mixture is short-circuited, all the chemical energy in the short-circuited mixture can be transformed into heat in the catalyst. The temperature of the exhaust gases thus increases by hundreds of degrees. The increased heat does not constitute a large problem for outboard motors, but for handheld engine applications such as brushcutters and chainsaws, the catalyst increases the hazard of fire and the risk of getting burned on engine details. Materials that can withstand the increased temperature will also be more expensive.

3 Experimental apparatus

When dealing with experimental work, the apparatus used for the experiments makes the difference between successful experiments and failure.

3.1 Engines

During the laborative work, three different engine designs have been used; one engine with open transfer channels (J625), one with two-port cup handle transfer channels (J630) and three different engines with different four-port cup handle transfer channels (Hva 901, Berema P95 std and Berema P95 mod). All engines had a transfer port design supposed to give a loop scavenging of the cylinder. The engine data will be presented later in this chapter.

3.1.1 Running conditions

The engines were run on their rated speed at wide open throttle with combustion during all measurements. For the Husqvarna engines, the rated speed was 9000 rpm, for the Berema engine 5800 rpm.

The reasons to run the engines at their rated speed with combustion are numerous: In motored engines, the temperature (and hence density and pressure) of the gas in the cylinder prior to the scavenging is significantly different from the conditions in a fired engine. At low engine speed, the dynamic effects are not present, and there is more time for the blow-down phase to take place, before the transfer ports open. This is crucial for the scavenging timing: Under realistic conditions, the blow-down phase is not over as the scavenging ports open, and the pressure in the cylinder is higher than it is in the crankcase, causing the flow to go from the cylinder down into the crankcase during the earlier part of the scavenging (scavenging delay). In a motored engine, the pressure is lower in the cylinder as the exhaust port opens than it is in the beginning of the compression phase, due to the heat transfer to the cylinder walls during the compression and expansion.

It is not easier to run the engine under realistic conditions than it is to motor it or run it at low engine speed: The window clogs from combustion and the mechanical stresses on the engine components grow significantly. To this can be added the sound level in the room where a two-stroke engine is run at full RPM at wide open throttle. These are probably the reasons that a lot of measurements on two-stroke engines have been performed on either low engine speed [6,20,28,30] or on motored engines [2,14,15,19,21]. There is however no doubt that the measurement quality can be done a lot better on engines running at unrealistic conditions.

Miles et. al. [25] has done a comparison of the flow fields in a motored engine and in the same engine under fired conditions. They found that the in-cylinder flow differed significantly if the engine was motored or fired.

3.1.2 Transfer channel designs

The design of the transfer channels is crucial for the engines capability to keep the fresh load in the cylinder. The difference between a good and a bad transfer channel design can make a difference of keeping 85 percent of the fresh load (for a good design) and 70 percent (for a poor design). That difference means that a poor engine emits nearly twice the amount of unburned hydrocarbons compared to a better design.

The difference in short-circuiting comes from the different flow behaviours in the cylinder during gas exchange.

3.1.2.1 Open transfer channels (J625)

The Jonsered 625 chainsaw engine is a three-port design, i.e. the inlet port is controlled by the piston position. J625 has got open transfer channels, one on each side of the cylinder.Open transfer channels are easy to manufacture, but gives the highest amounts of short-circuiting. The name open comes from the fact that one of the transfer channel walls is the piston or a cylinder lining. The distance for directing the flow is with this design very short. This leads to a poor flow direction within the cylinder and hence large risk of short-circuiting. Figure 7 is a photograph of the J625 cylinder.

According to the manufacturer, the full load short-circuiting is about 30 % on this cylinder design.

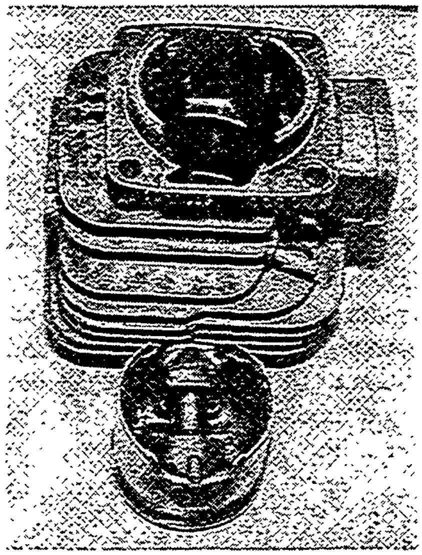

Figure 7 Picture of the cylinder of Jonsered 625 chainsaw engine. This cylinder is equipped with open transfer channels. To the right, the inlet port can be seen, and to the left the exhaust port. The small pipe from the transfer channel supplies pressure pulses from the crankcase to the fuel pump in the carburettor.

3.1.2.2 Cup handle transfer channels (J630)

Cup handle transfer channels are transfer channels that connects the cylinder and the crankcase with a channel that makes a turn out from the cylinder walls. The shape of the channels actually looks like cup handles (the cylinder is the cup). This design allows a longer leading wall, which means that the flow out from the transfer channels is more directed towards the "back" wall of the cylinder, away from the exhaust port.

The more beneficial flow in this design leads to an decrease in shortcircuiting from 30 % for the open transfer channels to about 15 % for cup handle transfer channels (according to the manufacturer). The J630 engine is shown in figure 8.

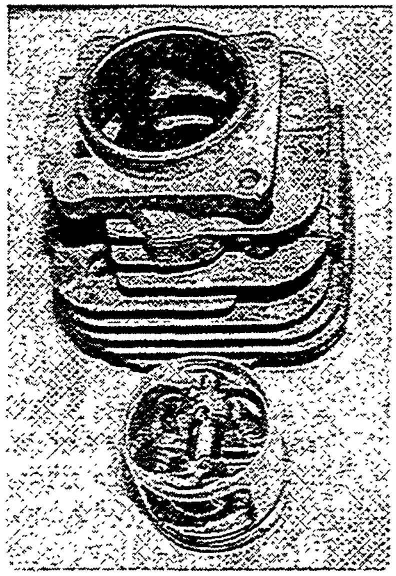

Figure 8 Picture of the Jonsered 630 chainsaw engine cylinder. This cylinder uses cup handle transfer channels that are casted with the entire cylinder. The exhaust port is seen to the right and the inlet port to the left.

3.1.2.3 Four port cup handle transfer channels

Three different engines with four port cup handle transfer channel arrangements were studied; one chainsaw engine (Husqvarna 901) and two engines for use in rock drills (AC Berema P95).

The use of four transfer channels gives an even better flow direction, and that can be seen in terms of trapping efficiency; the trapping efficiency in the four port cup handle design is almost 90 percent, according to the manufacturer.

3.1.3 Brake

When an engine shall run in a laboratory, it is necessary to take care of the power produced by the engine, if not idleing is the only load point to be studied. During the experiments, the engines were attached to water-brakes, i.e. brakes consisting of a flywheel with fins rotating in a chamber with water. The amount of water in the chamber gives the resistance of the brake and hence the power the brake consumes at a certain engine speed. The water is constantly changed, since the power from the engine heats the water. In most cases, the water outlet from the brake is in the bottom of the chamber and the water flows out from the pressure of gravitation. This arrangement gives a poor adjustability, since the water flow is poor. The solution to this problem was to increase the water-flow out from the chamber by pressurising it 3 bar (abs) with air during all experiments.

3.1.4 Crank angle encoder

In order to know the position of the crankshaft during engine operation, a crank angle encoder was attached to the crankshaft. A crank angle encoder gives basically two different signals, one at each revolution of the crankshaft (usually referred to as the TDC-pulse) and a number of pulses per crankangle degree. The crank angle encoder used in this application gave one pulse per crank angle degree and one TDC-pulse each revolution. At 9000 rpm, the frequency of the CAD-pulses is 54 kHz.

The signals from the crank angle encoder was used in all experiments, for the LDV measurements to deduce where in the cycle a velocity registration was made, and for the LIF and Laser Sheet measurements to trig lasers and cameras [3,10,11,12,13].

3.1.5 Optical access

All optical measurement techniques used in this study require optical access to the measurement area. In this investigation, the flow inside the cylinder was the subject of interest, so the cylinder had to be optically accessible.

The main targets when achieving optical access to the cylinder of an engine are:

- To alter the original shape and function of the cylinder as little as possible.
- To get as large area optically accessible as possible.

These two main targets are often hard to combine, since the space to drill holes and put windows in, often is very limited. Below is described how the engines were made optically accessible in two different ways, through the exhaust port and through the cylinder head.

3.1.5.1 Exhaust port

Two-stroke engines have a great way to get optical access to the cylinder: the exhaust port is open during a large part of the crankshaft revolution, and during that part, the scavenging of the cylinder takes place. The first way to get optical access was therefor to demount the silencer and run the engine without any silencing at all.

The exhausts constituted a big problem with this set-up. Since the two-stroke engine run with a richer than stoichiometric fuel mixture, the exhausts contain a high amount of CO, that is very dangerous to humans even in small concentrations. Worse than that, the exhaust gases also contain unburned hydrocarbons and oil particles that clog the measurement equipment if the exhausts were not taken care of.

The solution to this problem was to design an exhaust manifold that took care of the dangerous exhausts and in the same time kept the optical access without ruining the optical equipment. Figure 9 show the exhaust manifold.

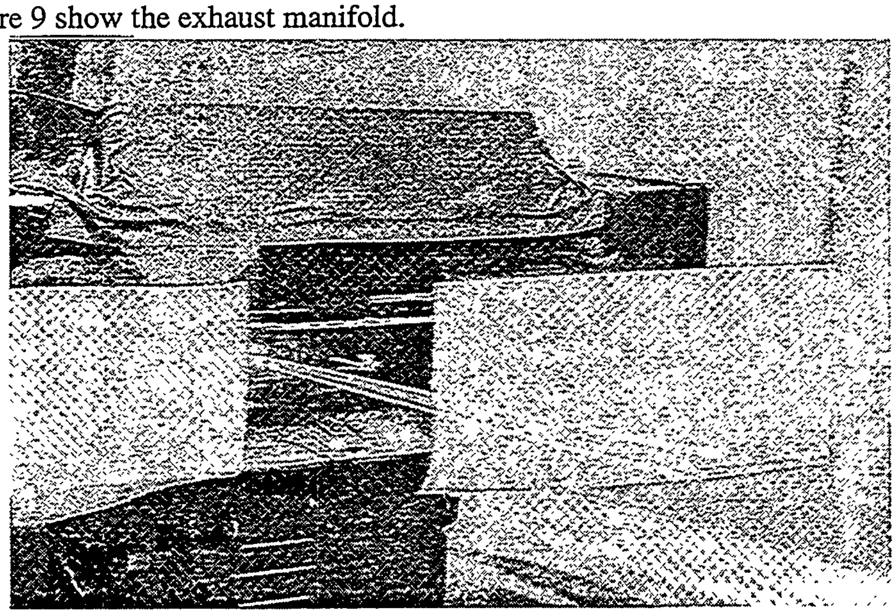

Figure 9 The exhaust manifold used during the experiments with the exhaust port as the optical access way. The dishcloths on the front of the manifold absorbed oil and prevented it from polluting the front lens on the LDV system.

3.1.5.2 Cylinder head

The LDV measurement technology used only allows measurements perpendicular to the measurement probe. Thus it was impossible to measure the in-cylinder flow velocity component that pointed towards the exhaust port using the exhaust port for optical access. To circumvent this problem, optical access was achieved through the cylinder head.

3.1.5.2.1 Window

To gain optical access to the cylinder through the cylinder head is unfortunately not as easy as through the exhaust: A window must be used in the place of the original cylinder head. Figure 10 shows the optical cylinder head.

The rough environment in the combustion chamber of a two-stroke engine running with wide open throttle at 9000 rpm demands a window with high strength. Furthermore, the sensitivity of the LDV-system in terms of window flatness adds to the demands on the window. A window quality fulfilling all demands is the Suprasil™ quartz windows manufactured by Hereaus, Four windows were bought (just in case the first three should break), in the thickness 25 mm and surface flatness $\lambda/10/cm^2$.

The sealing between the window and the cylinder end was made with a graphite gasket from Burgmann®. The gasket's thickness was 1mm, and in the mounting, it was compressed to 0.65 mm. Despite the rough environment, one graphite gasket lasted for many hours, and after the right gasket compression was tried out, not a single gasket blew.

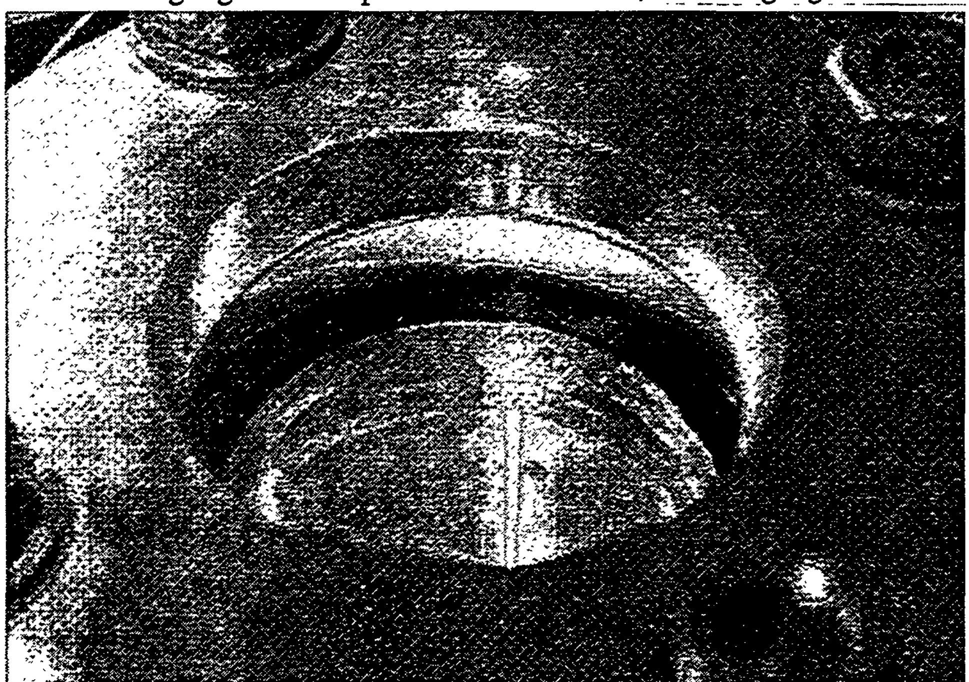

Figure 10 The engine running with the window in the top mounted. The LDV laser beams entering the cylinder through the window can clearly be seen, just as the spark plug location in the cylinder wall.

3.1.5.2.2 Ignition system

Since the top of the cylinder was replaced with a quartz window, it was not possible to use a central spark plug location, as was the case in the baseline engine. Instead, the spark plug was mounted in the cylinder wall. The first effort to run the engine with this new spark plug location showed that it was impossible to get the engine to run at its rated speed, 9000 rpm, even without load. The engine's unwillingness to run at high engine speed was due to the prolonged flame travel distance, and hence slower heat release rate.

The problem with the slow combustion was solved by mounting two spark plugs on opposite sides of the combustion chamber. The two spark plugs were fed with the same spark current, and coupled in a serial arrangement.

The limited space in the cylinder required small spark plugs. The choice fell on the NGK Me-8, a spark plug designed to fit in model engines with an M6-thread. This spark plug is shown in figure 11.

The baseline engine used a spark plug electrode distance of 0.8 mm, and the small spark plugs had an electrode distance of 0.4 mm, but since the small spark plugs were coupled in a serial arrangement, the same total spark plug electrode length was achieved.

The ignition timing for the modified ignition system was not altered from the baseline engine's ignition timing.

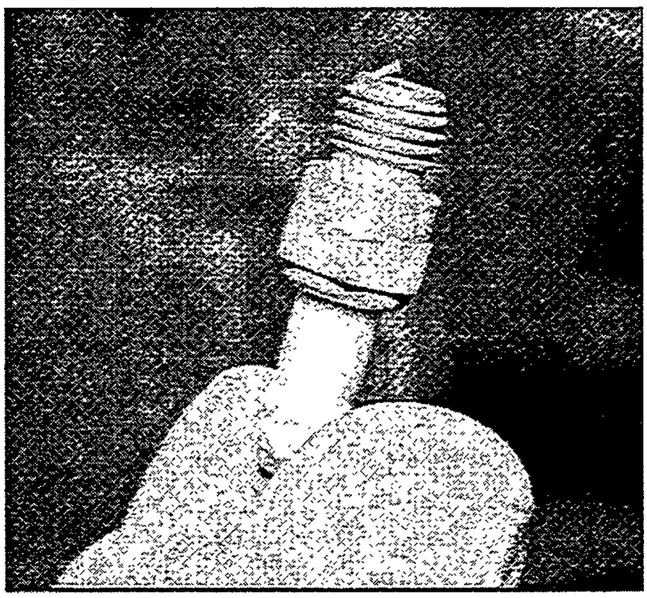

Figure 11 The NGK ME8 spark plug, and the author's thumb.

3.1.5.3 Fuel

The use of a window in the cylinder head is troublesome not only because the window easily breaks due to mechanical and temperature stresses, but the window surface against the combustion chamber also fouls from combustion. During running, the window gets hotter than the original cylinder head, and hence the risk for auto-ignition of the fuel also increases.The requirements of the fuel is therefor that it must burn clean, not to foul the window, and have a high octane rating, in order to prevent the increased risk of auto-ignition. The chosen fuel was isooctane, that by definition has got an octane rating of 100, and burns clean.

3.1.5.3.1 Seeding

LDV measurements and laser sheet droplet illumination requires the presence of particles in the flow to create a measurement signal. In most cases the choice of seeding compound is crucial to the measurement quality and window fouling rate.

In the case with running the two-stroke at full load and at a high engine speed, it turned out that the fuel and/or oil was not entirely vaporised as the fuel-air mixture entered the cylinder. The droplets in the air flow given by the carburettor served as seeding and made further seeding unnecessary. For all LDV measurements, the velocity measured actually is the velocity of the fuel particles rather than the air velocity, as is the case with all choices of seeding. Normally, the choice of seeding is crucial to the flow measurements due to the need for the particles to follow the air flow, but for the case with the two-stroke engine, the most interesting is the flow of the fuel itself. Therefore, the particle size is not as crucial as the case normally is for the seeding choice.

3.1.5.3.2 Lubrication

Small two-stroke engines usually use a mixture of gasoline and oil as fuel, and the engines tested here were no exceptions from that rule. The oil lubricates all bearings and the cylinder walls to prevent the engine from seizure. The oil content in the fuel constituted a large problem, since the oil fouled the window quite fast. To exclude the oil from the fuel mixture was impossible, since the engine would seize, probably in shorter time than the window would foul when the engine was run on ordinary oil.

The solution to the problem was to use a vegetable oil bought at the closest grocery store. The best of the oils tested, grape kernel oil, burns clean and has good lubrication features. The only problem with running the engine, except for the smell of kitchen that spread in the lab during the engine operation, was that the oil hardened in the carburettor and on the cylinder walls.

It was necessary to switch from the grape kernel oil towards a more regular two-stroke oil and run the engine with that oil for at least 5 minutes before it was shut off. This prevented the hardening of the grape kernel oil on the engine components and made it possible to use the same engine more than once.

3.1.5.3.3 Fuel Additive

Even after the original low smoke oil was replaced with the grape seed oil, the window fouled, although not nearly as much as prior to the change of lubricating oil. In order to get the windows even cleaner, a cleaning agent, Keropur®, was added to the fuel.

Keropur® is a fuel additive that is added in commercial gasoline to clean the internal surfaces of the engines. The combination of Keropur® and vegetable oil in the isooctane made it possible to run the engines for several hours without having to interrupt the measurements to clean the windows.

4 Measurement techniques

In this thesis, different laser based techniques have been used. The major advantages with using laser based methods are that they are non intrusive and can give high temporal resolution

4.1 Available measurement techniques for fluid flow

The most common method to measure fluid flow is the pitot-static tube. Unfortunately for the internal combustion engine application, the limited space restrains the use of pitot tubes, as well as most other mechanical meters. One exception from this rule is the Hot Wire Anemometer (HWA) measurement technique. HWA has proved to be able to measure flow velocities very accurately, but has one drawback: it is impossible to deduce the direction of the flow, and to measure two-phase flows. Furthermore, the piston's reciprocating motion along the cylinder walls makes it impossible to place HWA probes there.

The laser based techniques are mainly of two types: Doppler shift measurements techniques and Particle Image Velocimetry (PIV). The methods based on Doppler shifts are described in chapters 4.2-4.2.3.

PIV has aroused as a practically useful method with the increased computer power available, and the FFT (Fast Fourier Transformation) evaluation technique has been developed. The working principle of a PIV system is as follows: Two photos of the flow are captured with a delay of some very well known time. The two photos are then compared to each other to see the movement the seeding particles in the flow has undergone during the time between the two photographs.

The main disadvantage with the PIV is the small bandwidth, i.e. it is very difficult to measure a low velocity in one side of the measurement plane and a higher velocity in the other side.

4.2 Laser Doppler Velocimetry, LDV

LDV is probably the most mature laser based flow metering equipment. LDV was invented in 1964 by Yeh and Cummins [16]. They did not at all try to find a way of measuring flow velocities, but they were trying to detect the brownian movements by the use of two intersecting laser beams. Unfortunately, the measurements were disturbed by the presence of particles in the measurement area. This was of course annoying, but they soon saw the possibility of using the phenomenon to measure flow velocities in gases and liquids.

4.2.1 Operating Principle

The basic function of an LDV system is the intersection of two laser beams. In the intersection volume, that has the shape of an ellipsoid, a fringe pattern will occur. As a particle passes the fringe pattern, it will reflect light as it passes through a fringe with fluctuating intensity. The light frequency is given by the fringe spacing and the velocity of the particle. The fringe spacing can be calculated by the help of wavelength and intersection angle, and hence the velocity of the particle can be calculated if the frequency of light intensity fluctuations is known.

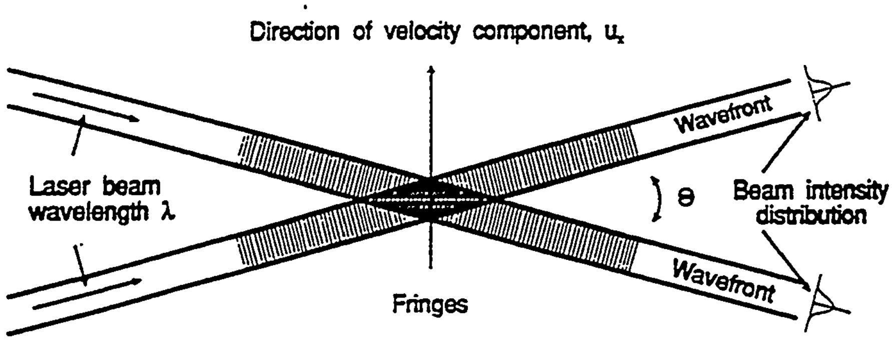

Figure 12 The fringe pattern formed by two intersecting laser beams [34].

The signal from the LDV system is a frequency signal. To extract velocity information from the frequency signal, the frequency must be multiplied with a calibration factor.
The calibration factor is calculated by:

$$d_f = \frac{\lambda}{2\sin(\frac{\Theta}{2})} \qquad (1)$$

were

λ = laser wavelength

Θ = angle between laser beams

As a particle crosses the fringe pattern, it scatters light which oscillates at the frequency ν_D

$$\nu_D = \frac{u}{d_f} = \left[d_f = \frac{\lambda}{2\sin\left(\frac{\Theta}{2}\right)} (1) \right] = \frac{2u\sin(\frac{\Theta}{2})}{\lambda} \qquad (2)$$

were u is the velocity component perpendicular to the fringe pattern and the measuring volume length. The velocity component u can then be obtained as

$$u = \nu_D \frac{\lambda}{2\sin(\frac{\Theta}{2})} \qquad (3)$$

This indicates that the velocity component can be obtained if the laser wavelength, angle between the intersecting beams and the frequency of light is known.
The measuring volume size is calculated as follows:
With the diameter of the laser beam in the focus given by

$$d_{e^{-2}} = \frac{4\lambda f}{\pi D_{e^{-2}}} \qquad (4)$$

where

f = front lens focal length

D_e^{-2} = beam diameter at the front lens

the measuring volume diameter d_m becomes

$$d_m = \frac{d_{e^{-2}}}{\cos(\frac{\Theta}{2})} \qquad (5)$$

The measuring volume length l_m becomes

$$l_m = \frac{d_{e^{-2}}}{\sin(\frac{\Theta}{2})} \qquad (6)$$

The number of fringes in the volume is given by

$$N_{FR} = \frac{d_m}{d_f} \qquad (7)$$

Usually, the number of fringes is above 10, which makes it easy to extract frequency information from the light burst collected.

To get the frequency of a light-burst, a number of methods can be used, such as the zero-pass counter, or just an ordinary counter. In the LDV system at Lund Institute of Technology, the Dantec® Burst Spectrum Analyser (BSA) is used. The BSA performs an FFT (Fast Fourier Transformation) on the burst signal.

4.2.2 Equipment

To perform LDV measurements, a large variety of different equipments can be used. In this chapter, the equipment and different set-ups for the equipment used during this work will be described.

4.2.2.1 Laser

The laser used was an Ar-ion laser from Spectra-Physics, model 2060. The maximum output was 5 W, and during the measurements, the laser was run at 1.5 W output.

The laser from Spectra-Physics emits laser light in three main lines of 514.5 nm, 488 nm and 476.5 nm. In this study, only the 514.5 nm (green) line and the 488 nm (blue) line were used. The third line, 476.5 nm can be used if a 3-D LDV system is used.

4.2.2.2 Optics

All LDV systems require emitting optics to form the two intersecting laser beams and collecting optics to acquire the signal from the intersection volume.

4.2.2.2.1 Emitting

In the used LDV system, the laser light is divided into two separate laser beams of equal strength by a Bragg cell. One of the beams is frequency shifted to make it possible to decide the direction o a velocity registration. The two laser beams are led to two fibres, which are connected to a probe. In the probe, the two laser beams are emitted through the same positive lens, and the intersection point is placed at the distance from the probe corresponding to the focal length of the lens.

In the measurements presented in this thesis, a lens of 600 mm focal length was used, and the beam spacing at the lens was adjusted to a minimum level, 14.25 mm. This gave us a calibration factor of 20 m/s/MHz, a measurement volume length of 7.5 mm and a measurement volume diameter of 0.1 mm. The LDV measurement settings are more thoroughly described in [11] and[12], enclosed as appendixes in this thesis.

4.2.2.2.2 Collecting optics

In this investigation, two different ways to collect the light signal from the measuring volume were used; backscatter (figure 13) and side-scatter (figure 14).

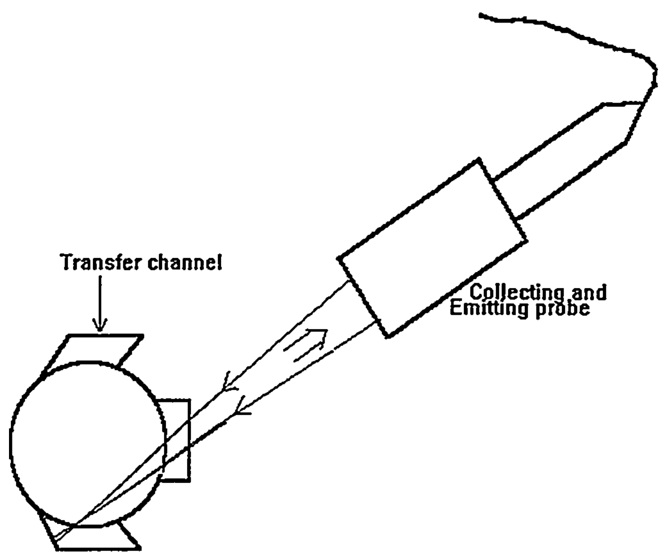

Figure 13Backscatter collection mode. The same lens emits and collects the light.

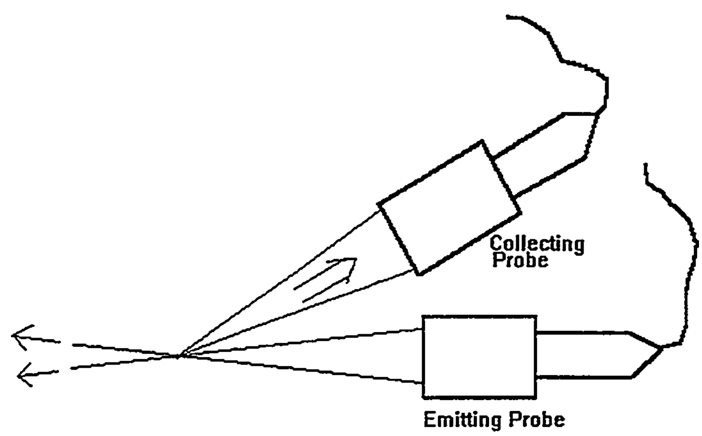

Figure 14 Side-scatter arrangement. The measuring volume is shortened by only collecting scattered light from the centre of the beam-intersecting.

The main difference with collecting the light from the side (side-scattering) and backscatter mode is the measuring volume length and the sensitivity for back wall reflections. Back wall reflections are the reflections from the wall behind the measuring volume. If the light from the back wall comes into the collecting device the signal to noise ratio will be reduced.

The recommended minimum distance to the back wall is 10 times the length of the measuring volume in backscatter mode. Since the measuring volume length was 7.5 mm with the front lens used in these experiments, the minimum length to the back wall would be 75 mm. Since the bores of the cylinders were about 50 mm, it would with this arrangement be impossible to perform LDV measurements in backscatter mode inside the cylinder. However, it was possible to use backscatter mode when the exhaust port was used for optical access, due to the cylinder wall's curvature. The light from the laser beams was not reflected towards the collecting lens except in the centre of the cylinder, where it was impossible to perform measurements.

4.2.2.3 Photo Multiplicator tubes, PM-tubes

After the light has been collected by the collecting device, the collected light is transported via a fibre to a PM-tube, where the light signal is transformed into an electric signal. The gain of this transformation is set by the voltage over the PM-tubes. In most cases, the voltage used was in the range from 600 to 900 volts.

4.2.2.4 Hardware Signal Processing

The electrical signal from the PM-tubes are recorded in the Burst Spectrum Analyser (BSA), where an FFT transformation is performed on the signal.

An FFT fits a function based on sines and cosines to the signal. From the fitted function, the frequency of the signal can be obtained. The frequency is then multiplied by the calibration factor (fringe spacing) and thereby the velocity is known.

In the BSA, there is an option to use an external time base, to decide when a velocity registration was made. This external time base consists of two different inputs, coupled to the outputs from the crank angle encoder. This way, it was possible to decide where in crank angle position each velocity registration was made.

4.2.2.5 Acquisition software

The acquisition software was bought from Dantec, and its basic function is to control the settings of the BSA and to collect the data from it. The program has got options to get different kinds of processed data, like spectral analysis etc., but these options were not used.

4.2.3 Data Processing

The Burst Spectrum Analyser saves all velocity registrations performed in one file, containing 196588 elements, with velocity and timing of each registration. The velocity registrations were then sorted in a vector were the element number corresponded to the CAD at which each velocity registration was performed. The mean velocity and RMS value were then calculated for each CAD, according to chapters 4.2.3.1.1 and 4.2.3.1.2. This gives a 3*360 matrix, were the first column is the CAD, the second the mean velocity for all velocity registrations performed at that CAD and the third column the RMS value of the velocity registrations at that particular CAD. A fourth row was added, giving a 4*360 matrix. The fourth row contained the number of velocity registrations.

After the data processing was finished, the results were presented by the use of the software package Matlab.

4.2.3.1 Definitions of turbulence and mean velocity

4.2.3.1.1 Mean velocity

The mean velocity is calculated by adding all velocity registrations collected at a particular crank angle degree and then divide that sum with the total number of registrations.

The mean velocity can be somewhat wrong due to a phenomenon called velocity bias. The velocity bias comes from a shortcoming in the LDV technique; if the particles in a flow (LDV measures on particles only) have different velocities (that is always the case in a turbulent flow), the particles with the higher velocity can pass the measuring volume more frequent than the slower ones. This will result in a higher calculated mean value than actually is the case.

Mostly, the velocity bias can be negligible, but one must always bear in mind its existence.

4.2.3.1.2 Turbulence

The word turbulence is very often used in engine discussions, but less often defined. All definitions of turbulence are very complicated, especially if different length scales like the integral length scale, the Kolmogorov scale and so on shall be described.

In LDV measurements, the turbulence is often defined as the Root Mean Square-value of all velocity registrations. This often turns out to be a reasonable estimate of the turbulence level.

The turbulence level reported in this thesis is calculated with the ensemble averaged definition, since it was impossible to cycle by cycle resolve the RMS-level. Cycle by cycle resolving of LDV measurements means that the mean velocity and the RMS value is calculated at each crank angle degree for all individual cycles. That way, it is possible to deduce both the flow fluctuations in one cycle and the variations from cycle to cycle.

Cycle by cycle resolving the measurements was however not possible in the measurements presented, due to the high engine speed, 9000 rpm. This means that on each individual cycle, too few velocity registrations were detected to get a reliable mean velocity.

The turbulence levels in this thesis is therefor the sum of both cycle by cycle variations and "true" turbulence.

The turbulence level can be used to determine if the seeding particle size is too large to follow the flow: If thhe seeding droplet size is too large to follow the flow well, the turbulence level increases substantially during large velocity fluctuations. This increase comes from the inertial forces large droplets have; if the air flow velocity decreases or increases very rapidly, the too large droplets will be less fast to adopt to the new velocity. Since the smaller particles will adopt faster, the RMS value will increase. No such indications could be detected for the measurements presented in this thesis. Hence can be concluded that the measured particles were small enough to follow the flow well.

4.3 Laser Sheet Droplet Illumination

Laser Sheet Droplet Illumination, LSDI, can be used to get an estimate of concentrations of droplets in a flow. The result is a two-dimensional image where the intensity in the image corresponds to droplet (particle) concentration.

4.3.1 Operating Principle

The basic principle of the laser sheet droplet illumination is the MIE scattering of light from particles. This phenomenon can easily be seen with the help of a strong pocket lamp a foggy night; if the beam of the pocket lamp is directed upwards, you can see the light spread from the water droplets in the fog. The object of this experiment was to get an image of the droplet concentration over the piston area to detect how much of the fresh mixture that escapes the cylinder through the exhaust port. The laser sheet was lead into the cylinder through the exhaust port, and the image of the light spread from the droplets was captured through the window in the cylinder head.

4.3.2 Equipment

The equipment used in this test is basically a laser, some optics to form a sheet of light from the laser and an image intensified CCD-camera to capture an image of the illuminated sheet.

4.3.2.1 Laser

The laser sheet was by the same continuos laser that was used as light source in the LDV measurements. The laser was, as mentioned in the LDV chapter, an AR-ion laser with a specified output of 5 W in all lines. During the laser sheet measurements, the laser was run at its maximum output, that, since the laser tube was brand new, was about 6.5 W.

4.3.2.2 Optics

To create a laser sheet and capture an image of the droplet concentration, both emitting and collecting optics must be used.

4.3.2.2.1 Emitting

The emitting optics formed a sheet from the laser beam and lead the sheet into the cylinder through the exhaust port. The configuration can be seen in figure 15.

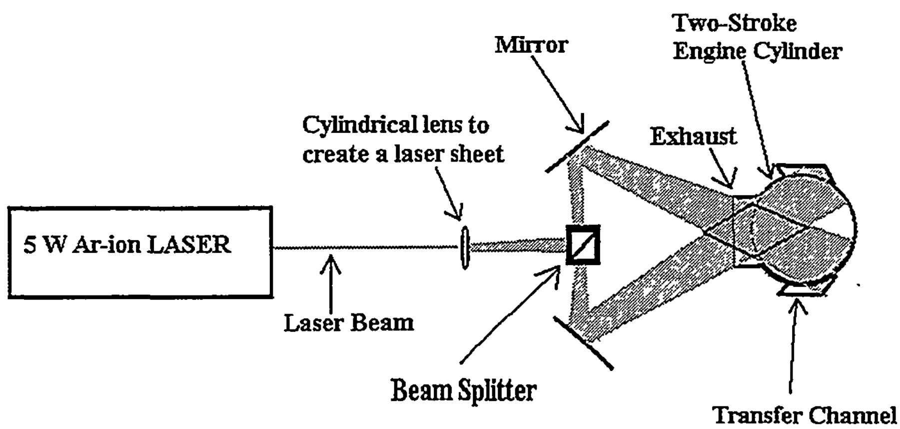

Figure 15 The emitting optics set-up. The beam splitter arrangement and the two mirrors were used in order to cover a larger area of the cylinder bore.

4.3.2.2.2 Collecting

The image was captured through the window in the cylinder head. Just in case the window would break during engine operation, the camera was placed not above the window, but beside the engine, by the use of a plane mirror in 45° angle.

4.3.2.3 CCD-Camera

A CCD-camera (Charge Coupled Device) is a camera that has a chip as the light sensitive area. The output from it is a matrix of 576 times 384, with an intensity scale from 150 counts up to 16384 for each element or pixel.

The camera used in this experiment was made by Princeton Instruments, and was equipped with an Image Intensifier (see chapter 4.3.2.3.2)

4.3.2.3.1 Lens

A standard Nikon zoom lens with a variable focal length of 70 to 210 mm was used. The use of a zoom lens makes the optical set-up much more simple to use, since the magnification can be varied continuously within the limiting focal lengths.

4.3.2.3.2 Image intensifier

An image intensifier consists of a photocathode, a micro-channel plate (MCP) electron multiplier, and a phosphor plate, all positioned in front of the CCD. Electrons are ejected from the photocathode in response to incident photons, and accelerate toward the phosphor or MCP input. The number of electrons is increased by the gain of the MCP. The resulting electron image is incident on the phosphor screen, which emits many photons for each incident electron. Thus for each photoelectron many photons are available to the CCD.

A camera equipped with an image intensifier is much more sensitive to light and allows usage of shorter exposure times than an ordinary camera. The camera used here had a shortest exposure time of 5 ns. The used exposure time was set to 8 μs, which corresponds to about 0.4 crank angle degrees at 9000 rpm. The reason that a shorter exposure time was not used was the laser light intensity. The laser used was a continuous laser, which does not give sufficient light to reduce the exposure time significantly shorter than 8 μs, if a reasonable signal to noise ratio is wanted. On the other hand, a longer exposure time would reduce the temporal resolution.

4.3.2.3.3 Software

The camera was run with the help of software from the manufacturer of the camera, Winview 1.4.1.

4.3.3 Data Processing

The image processing and presentation were made in the program package Matlab, which allows a large variety of presentation options.

4.3.3.1 Background subtraction

The background level of the CCD chip is about 200 counts, and the maximum level 16384 counts. The background noise was subtracted from the signal matrix.

In order to adjust the resulting image so that the differences in the laser sheet intensity are taken into account, an image was captured when the cylinder was filled with smoke. This image was meant to be used as the dividend in an image processing, where each image should be divided with that image, as mentioned to adjust for the difference in laser sheet intensity over the cylinder bore. This approach did however fail, the resulting images made no sense at all, and hence only non-processed images are shown. The reason for the failure with the approach described was probably the scattering of the signal light that occurred since the image was captured in a totally smoke-filled cylinder.

4.3.3.2 Program description

The program was, as mentioned, written in Matlab, and consists of a subroutine that reads the output file from the CCD camera and one drawing routine that displays the result. The Matlab program offers a large variety of displaying options, as for example different colour images, isoclinal lines, etc. etc.

4.4 Laser Induced Flourescence, LIF

The work presented in this chapter, LIF measurements in the exhausts of the two-stroke engines, were mainly performed by Öivind Andersson, Greger Juhlin and Marcus Alden'n from the division of Combustion Physics, with some engine assistance from Martin Ekenberg and Bengt Johansson from the division of Combustion Engines.

4.4.1 Operating Principle

The working principle of LIF is that a laser pulse excites a molecule or atom to a higher energy level. When the molecule or atom returns to its normal state, it sends out light of a wavelength different from the exciting laser wavelength.

The light that results from the return back to the normal state is called flourescence.

If the presence of so called minor species (NO, C, NO_2) are to be measured, a tunable laser that excites that specific atom or molecule must be used.

During the measurements, the object was to measure the fuel content in the exhausts as a function of crank angle degree, and a somewhat more simple measurement method was used; 3-pentanone, that has vaporising heat and boiling point very close to those of isooctane, and fluoresces when excited with a 248 nm excimer laser, was added to the fuel.

The measured area was just outside the exhaust port, and the laser shots were triggered by the crank angle encoder. The time for one measurement (laser shot length) was about 17 ns. This corresponds to about one thousand of a crank angle degree.

4.4.2 Equipment

4.4.2.1 Laser

The laser used in this experiment was a KrFl excimer laser. The laser was tunable, and the tuning was set to 248 nm. The pulse energy was 250 mJ and the pulse duration 17 ns.

4.4.2.2 Emitting Optics

During the experiments, two different experimental set-ups were used; one to image the fuel content outside the exhaust port to get information on irregularities in the exhaust glow, and one set-up for spectral measurements. The emitting optics differed slightly for the two set-ups, for the imaging measurements the laser sheet was laying outside the exhaust port and the laser sheet was focused with help of a cylindrical lens.

In the spectral measurements, it was found that the focused laser beam cracked the hydrocarbons in the fuel to smaller ones that fluoresced and thus destroyed the measurements. Therefore, a non-focused laser sheet was used for the spectral measurements. A non-focused laser sheet gives a weaker signal than a focused one, but as the focused laser sheet destroyed the hydrocarbons it could not be used.

4.4.2.3 Collecting Optics

For the imaging experiments, a UV lens (UV Micro Nikkor 105-4,5) from Nikon was used, and the images were captured via a mirror (see paper 961927).

4.4.2.4 CCD-Camera

The CCD camera used for the LIF measurements was the same camera that was used for the laser sheet experiments.

4.4.2.5 Spectrograph

For the spectroscopic measurements, the set-up was a little bit more complicated. The presence of particles in the exhaust gases makes the MIE scattering signal very strong compared to the LIF signal, and hence the MIE signal must be suppressed. This was done with a butylacetate filter between the collecting optics and the measurement volume.

To perform spectrographic measurements, a spectrograph is necessary. A spectrograph basically consists of a lattice and a slit to let the light in to the lattice. The smaller the slit is, the higher the resolution will be, but the signal level will as well decrease for decreasing slit width.

A spectrograph is used to get information on the wavelength content in the fluorescence signal. The spectrograph was during the LIF measurements used to differ the fluorescence signal from the fuel tracer (3-pentanone) from the fluorescence from the lubricating oil. The method of doing this was simply to run the engine on fuels containing different amounts of 3-pentanone and to subtract the fluorescence spectrum acquired with addition of 3-pentanone to the fuel with the fluorescence acquired without the fuel tracer. By doing this on several different crank angle positions, the relative amount of short-circuiting of fuel as a function of crank angle degree could be observed.

3-pentanone was chosen to be the fuel tracer because it fluoresces in visible wavelengths and has vaporising characteristics very close to those of isooctane [26]. The visible fluorescence makes it easier to capture images, since it is possible to use standard imaging lenses. For other fuel tracers (i.e. toluene), the fluorescence is mainly in the ultra-violet wavelengths, which makes it necessary to use special UV grade lenses to be able to catch the images.

5 Results

The results from the measurements were presented at different SAE meetings, and the papers from those meetings are included in this thesis. The object with this chapter is to "make a sum of the components", i.e. to see whether the results from the different measurement techniques agree or not.

5.1 Measurements performed in chronological order

The most simple method to perform optically based in-cylinder measurements in a two-stroke engine is to use the exhaust port as the optical access way. Therefore, it was natural to begin the LDV measurements with that approach. This type of measurements were performed on four different engine types: Two almost identical engine prototypes from AC Berema and two very different chainsaw engines from Husqvarna Forest and Garden.

After the LDV measurements through the exhaust port, the excimer laser from Dept. of Combustion Physics was available, and the LIF measurements outside the exhaust port commenced.

After the LIF measurements, the work with making the engine optically accessible through the top of the engine started. This took a substantial amount of time, mostly due to the problems with the slow combustion using the non-central spark plug location. Work with optical cylinder heads were made on five different cylinders, the two Berema cylinders and three different chainsaw cylinders.

The last measurements performed were the laser sheet droplet concentration measurements. Those measurements were performed on four different engines: One Berema cylinder and three Husqvarna cylinders.

On the following pages, results showing scavenging timing, scavenging flow velocities and scavenging flow directions out from the transfer ports are presented. These results are compared to the expected scavenging flow behaviour for loop scavenged engines.

5.2 Flow directions out from transfer ports

The cylinder drawings show the wanted flow direction out from the transfer channels, that is supposed to give an acceptable loop scavenging. Unfortunately, the drawing material is confidential and can therefor not be printed here, but the wanted flow direction angles does not differ much from the angles normally used in loop-scavenged designs [4].

5.2.1 Expected flow behaviour

What is wanted and expected from the flow is of course that the flow out from the transfer port is directed as the ports are. This is supposed to give a good loop scavenging.

Gordon P Blair at the Queens University of Belfast has done a substantial amount of work on these angles, and has found that for good loop scavenging

- The upsweep angle (UPM) of the transfer channel is not above 10°.
- The value of AM2 is usually between 50° and 55°, which means that the E1 angle is 35° to 40°.
- The target point MT2 is usually between 10% and 15% of the cylinder bore dimension.

on a design with a good scavenging [4].

In figure 16, the above listed variables are defined.

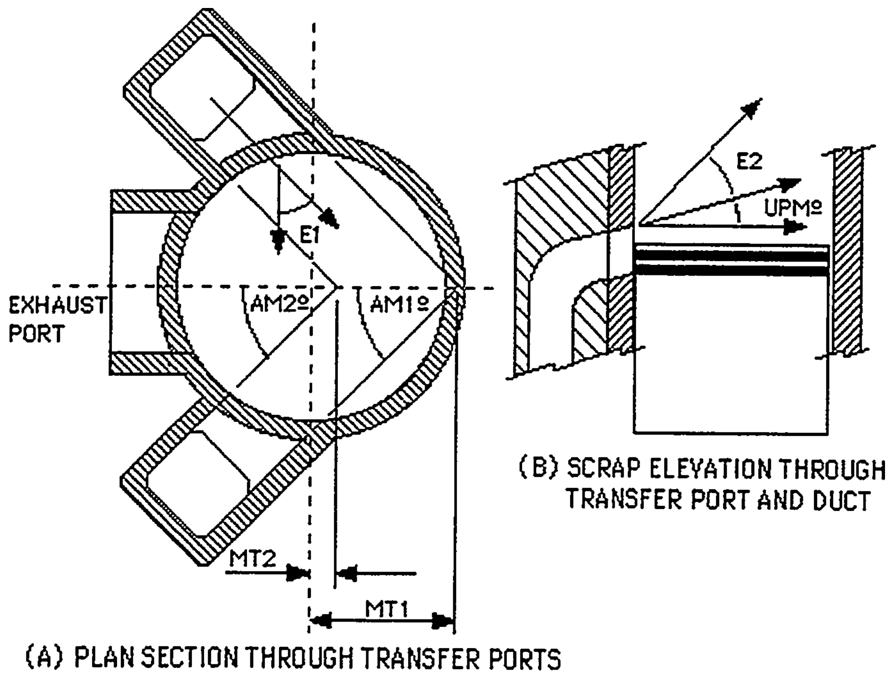

Figure 16 Description of the angles E1 and E2 and the target points MT1 and MT2 [4].

5.2.2 Measured flow behaviour

The effective E1 and E2 angles, that is the angle at which scavenging air enters the cylinder, (see figure 16) were measured with the LDV system in two types of cylinders; one with open transfer channels (Jonsered 625) and one with cup handle transfer channels (Jonsered 630).

5.2.2.1 LDV through exhaust port

The LDV measurements through the exhaust port made it possible to deduce the E2 angle. The LDV measurement was performed just outside the transfer port, and the result shown is a mean value of many cycles.

The resulting angle is shown as a function of crank angle degree for the two cylinders J625 and J630 (open and cup handle transfer channels respectively).

As figures 17 and 18 show, the E2 angle is much larger for the J625 cylinder (open transfer channels), meaning that the flow out from the transfer ports is more directed towards the top of the cylinder than the case is for the J630 cylinder, where the flow is more parallel to the piston top.

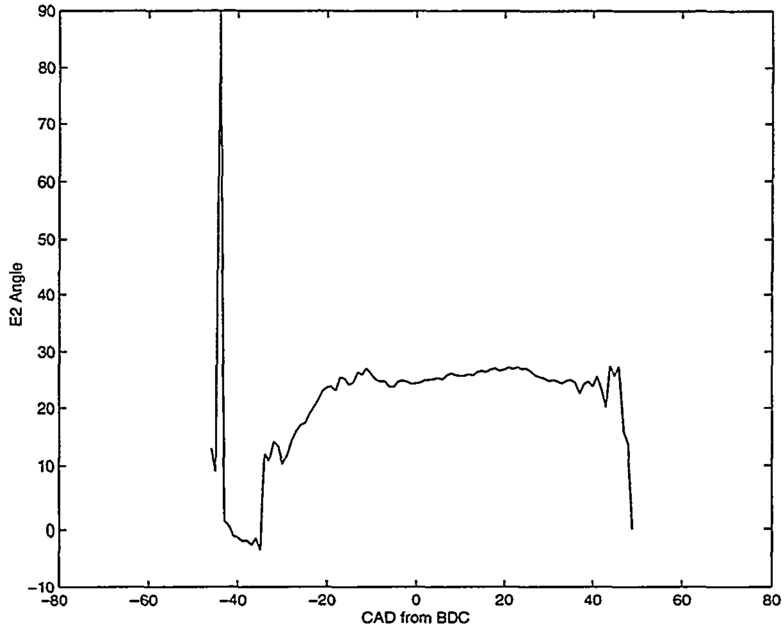

***Figure 17** The vertical flow direction angle (E2) as a function of CAD in the J625 cylinder (open transfer channels). The large diversions of the angle in the beginning and in the end of the scavenging phase is due to incomplete numbers of velocity registrations.*

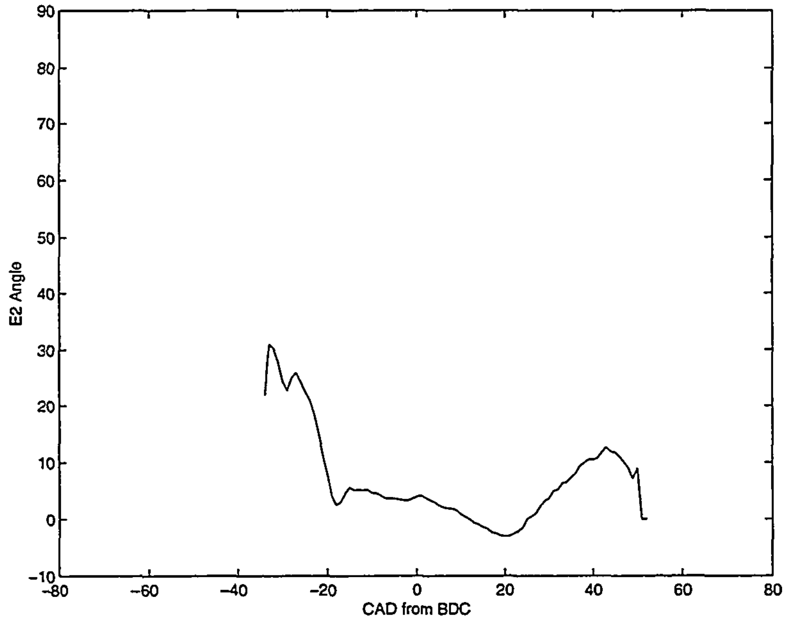

***Figure 18** The vertical flow direction angle E2 as a function of CAD for the J630 cylinder (cup handle transfer channels). The flow direction is more parallel to the piston top for this cylinder, which gives a better cooling of the piston.*

5.2.2.2 LDV through cylinder head

As mentioned earlier, LDV technique is only able to measure flow velocity components that is perpendicular to the measurement probe. This makes it impossible to deduce the angle E1 when using LDV with optical access through the exhaust port. That is however possible when the optical access is provided through the top of the cylinder. Figures 19 and 20 show the angle E1 (see figure 16) as a function of crank angle degree. Note that the angle for the cylinder with cup handle transfer channels is much larger at all crank angle positions than it is for the open transfer channel design. The larger angle for this cylinder compared to the open transfer channel shows that the flow out from the transfer channels is more directed towards the back wall of the cylinder. It can be noted that the angle is between 20 and 40 degrees during the major part of the scavenging. According to Dr Blair, the best flow direction is 35-40 degrees [4].

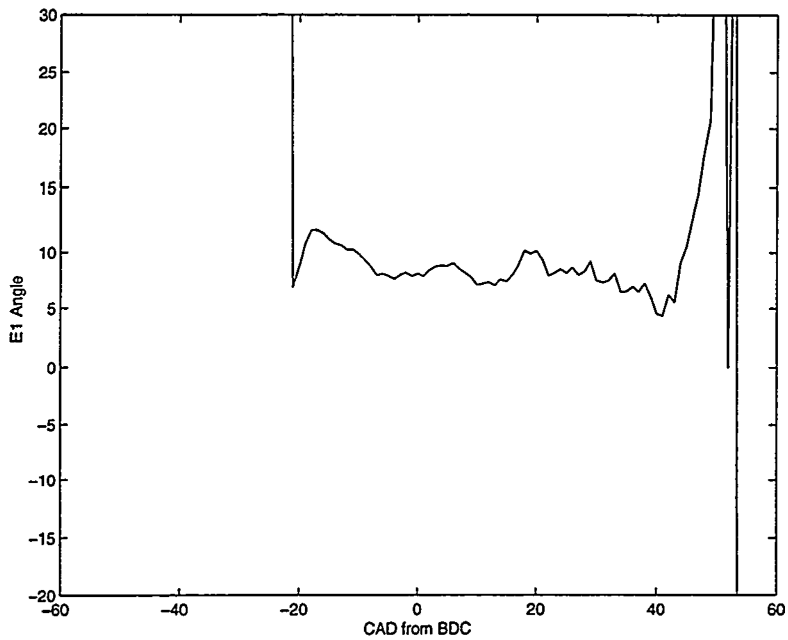

***Figure 19** The horizontal angle E1 as a function of CAD for the cylinder with open transfer channels (J625)*

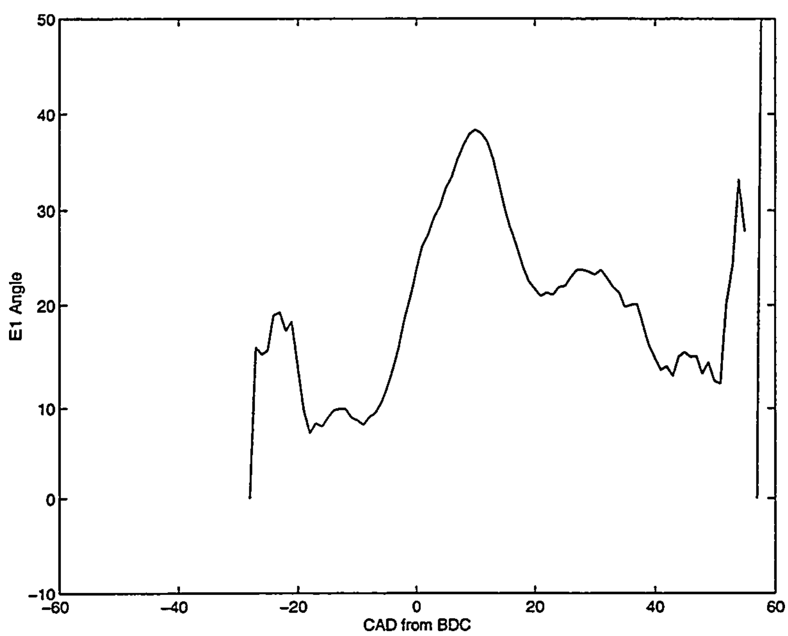

***Figure 20** The horizontal angle E1 for the cylinder with cup handle transfer channels as a function of CAD.*

5.2.2.3 Laser Sheet

From the laser sheet images, the E1 angle can be obtained, however not resolved as a function of CAD, only if the fuel droplets does not vaporise to the exhaust port. In the open transfer channel cylinder, this happens. Therefore, it is impossible to obtain any kind of angular information of the flow field in the cylinder with open transfer channels.

In the cylinder with cup handle transfer channels, the flow direction angle can be measured, and the result agree well with the LDV measurements.

5.2.3 Comparisons and discussions

The flow angle just outside the transfer port is most accurately measured with LDV, the angle E2 with the exhaust port as optical access way and the angle E1 with the cylinder head as the optical access way.

The laser sheet droplet concentration measurements can give the average E1 angle but this method seems quite unreliable, due to the vaporisation of the fuel droplets close to the exhaust port.

5.3 Fulfilment of loop-scavenging

The idea with loop scavenging was proposed by the German engineer Schnürle in 1926, in order to reduce the scavenging losses and being able to use a flat piston top.

5.3.1 Expected flow behaviour

The expected flow behaviour for a loop scavenged engine is described in chapter 2.2.3.2. This chapter is describing the desired flow (for loop scavenging) in the planes that have been measured with the LDV equipment

5.3.1.1 LDV through exhaust port.

The measurements through the exhaust port were performed in three measurement planes; one plane in the centre of the cylinder, one 10 mm inside it and one 10 mm outside it (see figure 21). The measurements were performed at the four heights 3,5,7, and 9 mm over the piston top at BDC. These three measurement planes make it possible to deduce the presence of the expected loop scavenging behaviour.

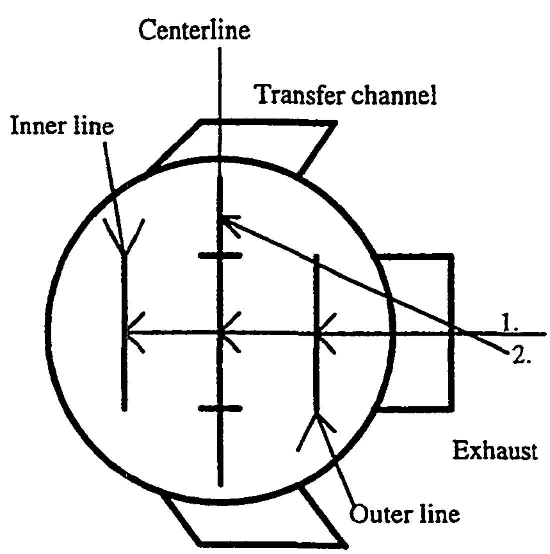

Figure 21 The three measurement planes used when the flow behaviour was measured through the exhaust port [11].

If a loop scavenging is present, the resulting flow pattern in the three measurement planes would be as follows:

- Along the inner line, the flow will be directed mainly upwards, at least in the middle of the plane.
- In the centre line, the flow out from the transfer ports will be clearly visible in the both ends, and in the middle the transfer channel jet will miss the LDV measurement volume and hence give no or lower velocity registrations.
- In the outer plane, the flow velocities are supposed to be low, and eventually a flow from the top of the cylinder will commence late in the scavenging phase.

Figure 22 show the expected flow behaviour for the three measurement planes.

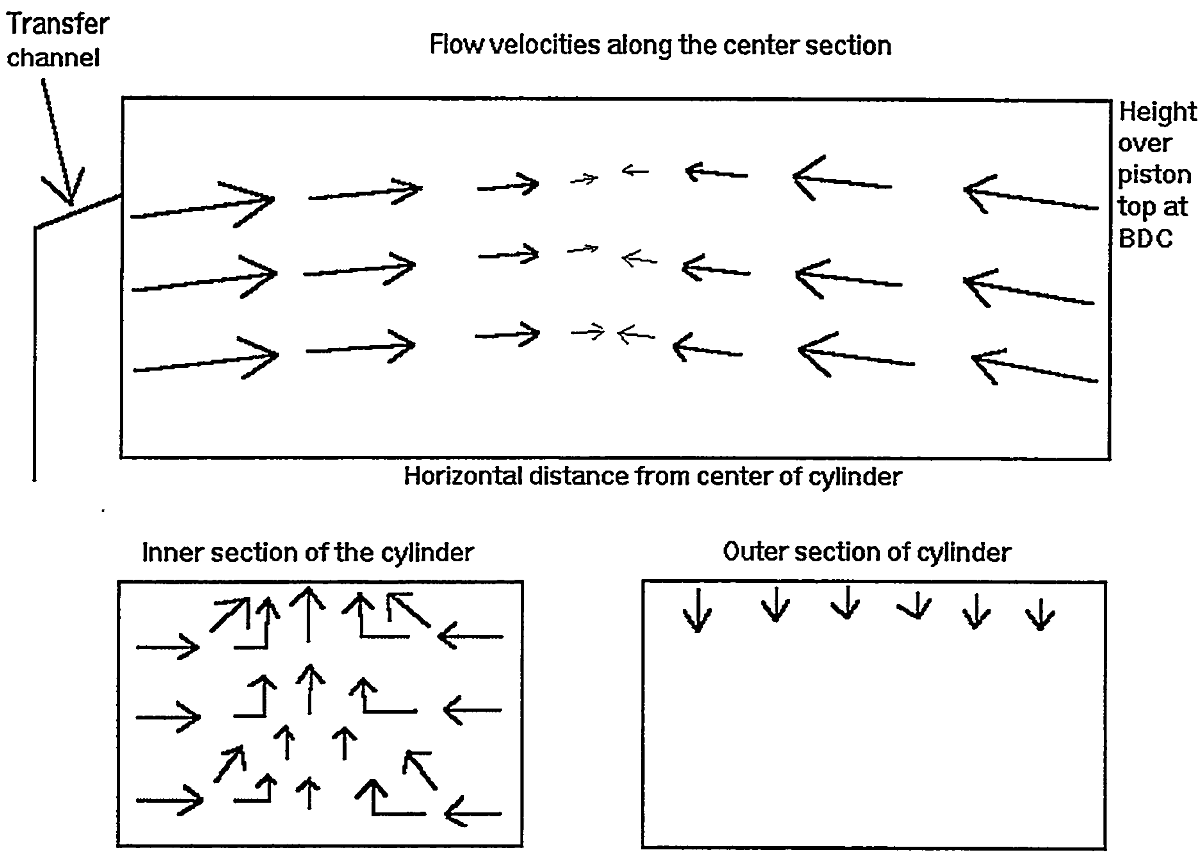

Figure 22 The expected flow behaviour along the three measurement planes when measured through the exhaust port.

5.3.1.2 LDV through cylinder head

The expected flow pattern for the LDV measurement through the cylinder head is more obvious than the expected flow pattern for the LDV measurements through the exhaust port: the flow is supposed to be directed from the transfer ports towards the "back" wall of the cylinder. At the back wall, the flow is supposed to turn upwards against the cylinder head. This flow component cannot be measured through the cylinder head.

One important phenomenon that can occur at the point where the two jets from the transfer channels meet is that the flow does not turn upwards, as it is supposed to, but towards the exhaust port. If this happens, that flow component can be measured through the cylinder head.The expected flow for the measurements through the cylinder head is shown in figure 23.

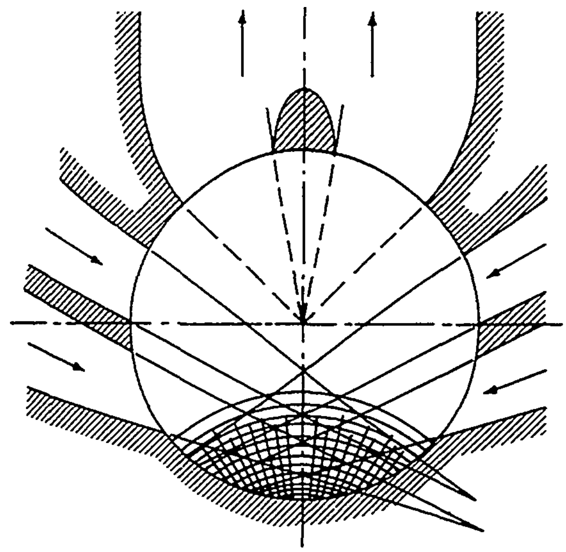

Figure 23 The expected flow pattern when LDV measurements are performed through the cylinder head [22].

5.3.1.3 LDV outside the exhaust port

LDV is not only able to measure flow velocities, but the results can also be used to get an estimate of the particle concentration in the flow. However, the different scattering characteristics of particles with changing size and shape will limit the information of the particle concentration to a relative measure.

When measuring the velocities outside the exhaust port, it can therefor be interesting to see when, during the cycle, the particles are emitted from the engine. If one presumes that the burned gas contains no particles but the fresh gas does, the concentration of particles can be assumed to be higher outside the exhaust port at closure time than in the beginning of the scavenging phase if the engine is properly loop scavenged.

Since it is known that the cylinder with open transfer channels has more short-circuiting, and it is rather obvious that most part of the short-circuiting takes place late in the scavenging phase, the cylinder with open transfer channels is expected to show more velocity registrations later in the scavenging phase, relative to the cylinder with cup handle transfer channels.

5.3.1.4 LIF outside the exhaust port

The LIF measurements outside the exhaust port are supposed to give the same results as the LDV measurements outside the exhaust port, with one major difference: The LDV measurements does not give any information about the content in the particles. LIF can give that information, with the help of spectroscopic analysis of the fluorescence signal.

The object with the LIF measurements was to differ the short-circuited hydrocarbons from hydrocarbons due to incomplete combustion. It could be expected that the results would show that a larger part of the total hydrocarbons is due to short-circuiting losses for the cylinder with open transfer channels than for the cylinder with cup handle channels.

5.3.1.5 Laser Sheet

The laser sheet concentration measurements would probably give a good estimation of the loop scavenging if the gaseous fuel concentration could be measured and not, as the case was for this measurements, only the liquid phase.

As it turned out, the fresh gas escaping the cylinder can not be imaged, and this means that the only obtainable information on the fulfilment of the loop scavenging effect is the E1 angle that can be measured on the resulting images.

5.3.2 Measured flow behaviour

5.3.2.1 LDV through exhaust port

The LDV measurements through the exhaust port were performed on five different cylinders; two from Berema and three different cylinders from Husqvarna.

All cylinders, except one, were equipped with cup handle transfer channels. To show the very large variety in the flow behaviour, two different flow patterns will be shown; the flow pattern from the J625 (open transfer channels) and the J630 (cup handle channels). Those two cylinders were chosen since they only differ in terms of transfer channel design, and are identical from all other points of view, like bore, stroke and port timings.

The results are presented in [11]. Figures 24 and 25 show typical scavenging patterns for the cylinders with open and cup handle transfer channels respectively. Note that along the inner section of the cylinder, the flow turns upward for the cup handle transfer channel cylinder (J630). This is not the case for the cylinder with open transfer channels. Note as well that the RMS level increase as the two jets from the transfer channels meet in the cylinder with cup handle transfer channels. For the cylinder with open transfer channels, the RMS level is more evenly distributed in the cylinder.

5.3.2.2 LDV through cylinder head

The LDV measurements with the cylinder head as the optical access way were also performed on the five cylinders mentioned in the previous chapters. Here, results from the two Husqvarna cylinders J625 and J630 are presented.

As can be seen in figures 5.3.2.2.1 and 5.3.2.2.2, the difference between the two cylinder designs is quite obvious; the cylinder with cup handle transfer channels has a very clear loop scavenging pattern, with the transfer jets directed away from the exhaust port. The cylinder with open transfer channels does not show any direction towards the back wall at all. This explains the higher amount of short-circuiting of the fresh gas.

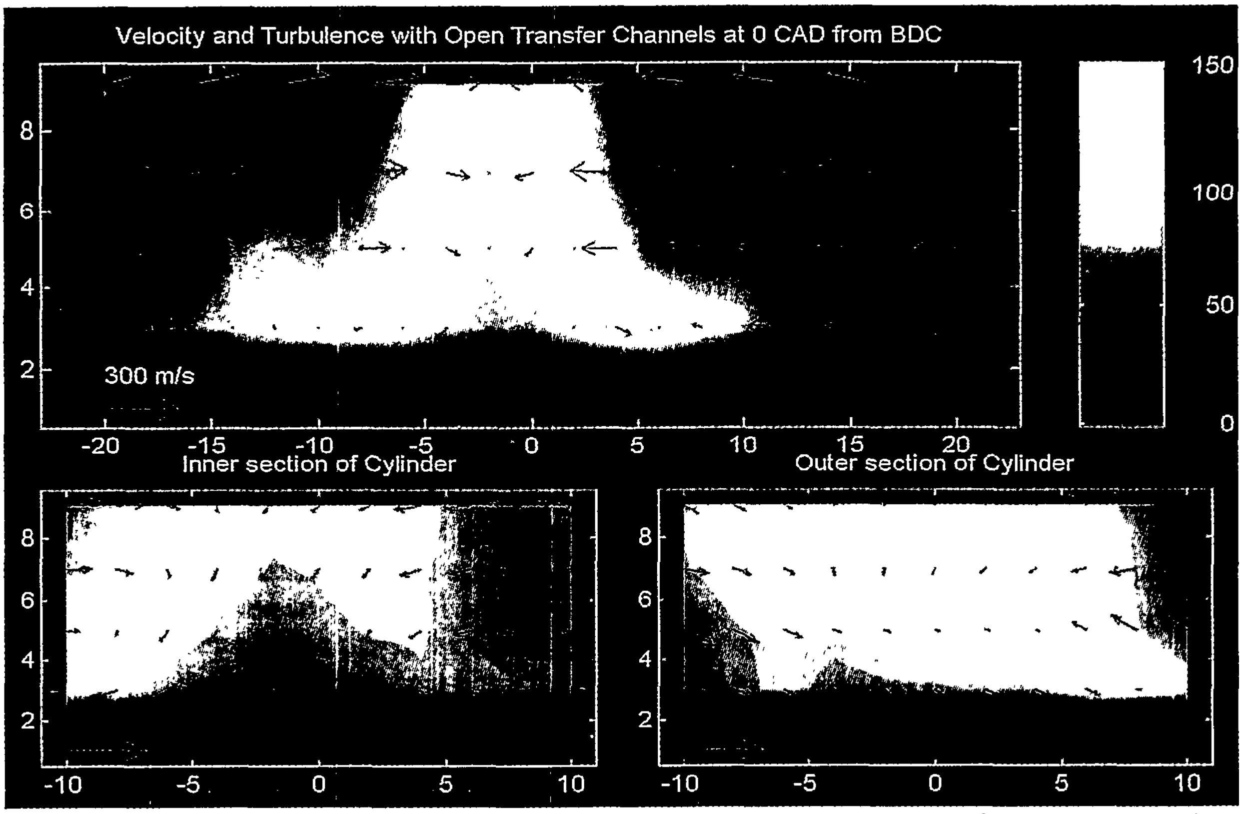

Figure 24*The flow field in the J625 cylinder at BDC The colour-scale in the image show the RMS levels in the flow (turbulence level. All white means a turbulence level of 150 m/s.*

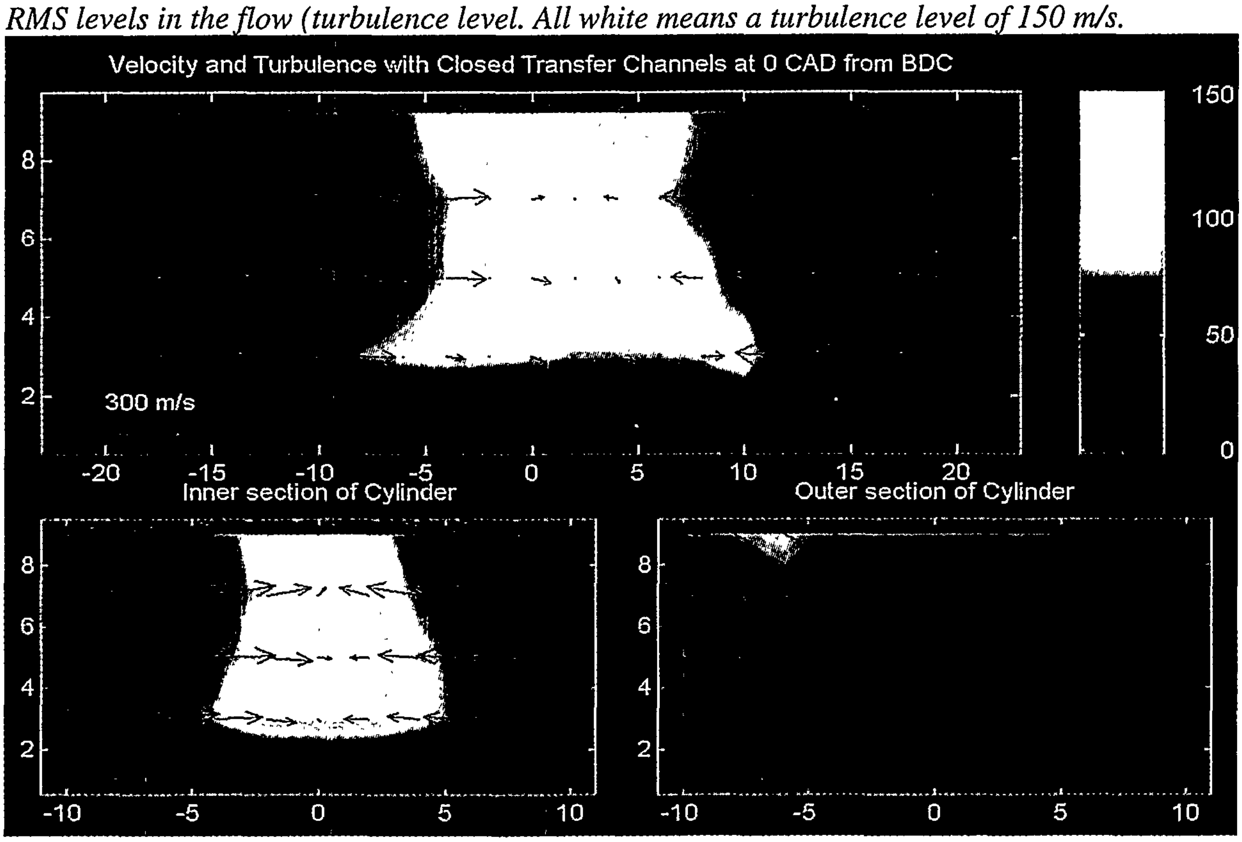

Figure 25 *The flow field in the J630 cylinder at BDC. The colour-scale in the image show the RMS levels in the flow (turbulence level. All white means a turbulence level 150 m/s. For this cylinder, the flow field is very similar to the flow field assumed in a loop scavenged engine.*

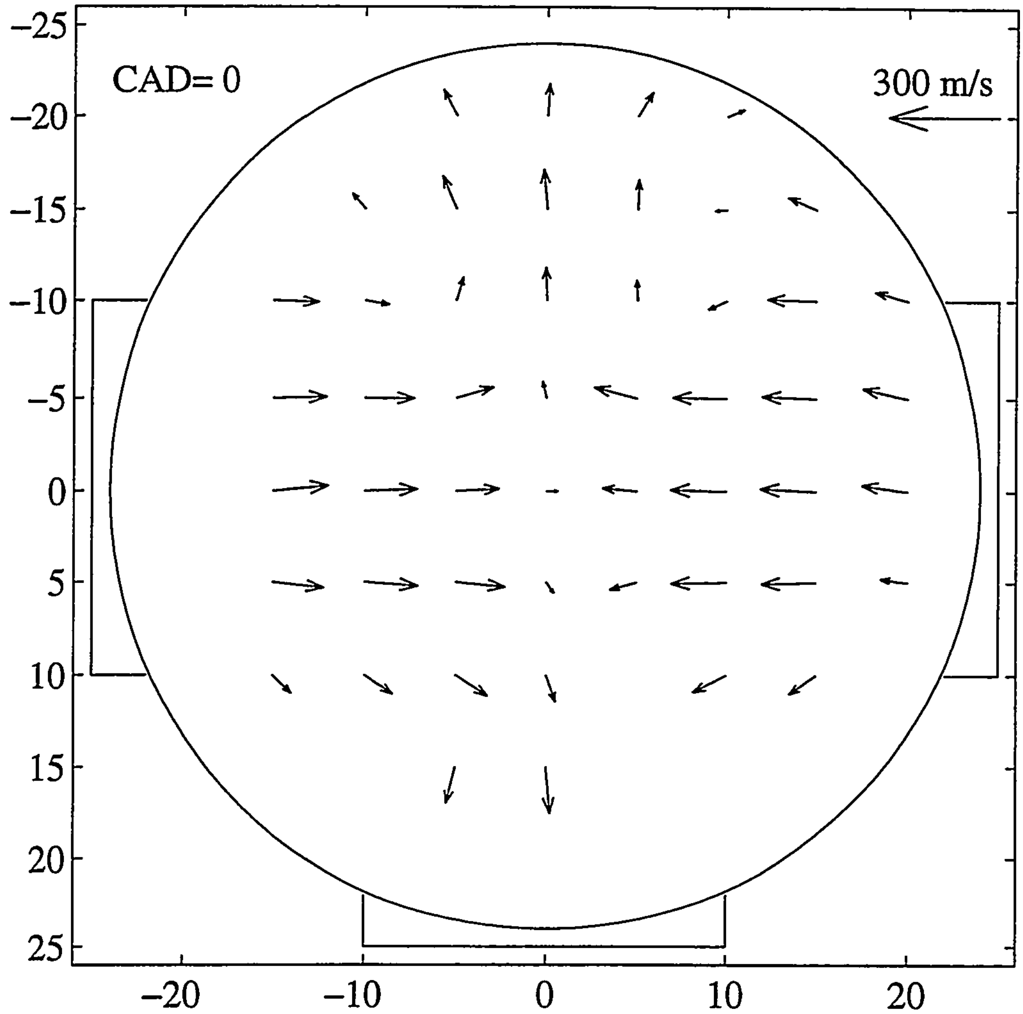

Figure 26 *Typical flow pattern when measuring with LDV through the top in the J625 cylinder (open transfer channels). This figure shows the flow pattern at BDC 5 mm over the piston top at BDC [12].*

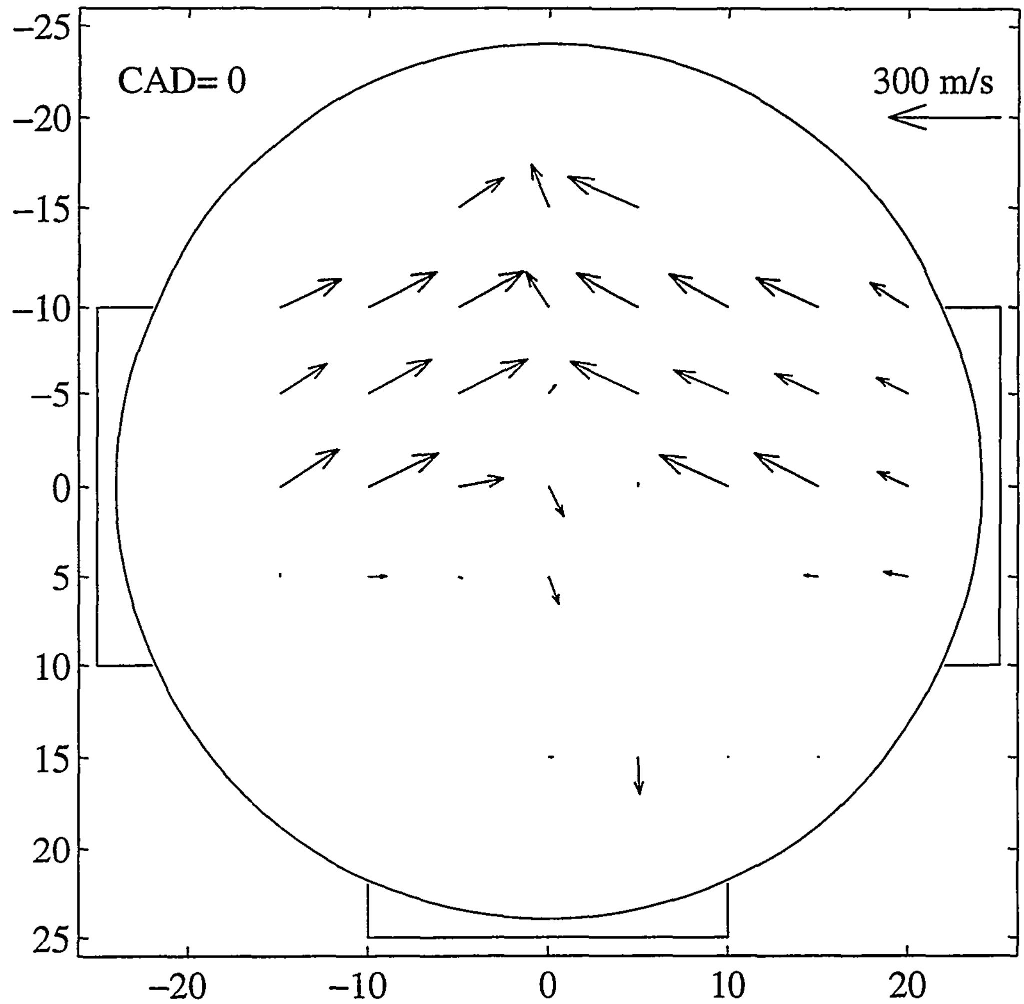

Figure 27 Typical flow pattern when measuring with LDV through the top in the J630 cylinder (cup handle transfer channels). This figure shows the flow pattern at BDC 5 mm over the piston top at BDC [12].

5.3.2.3 LDV outside the exhaust port

Outside the exhaust port, it is very hard to tell anything about the in cylinder flow behaviour, but at least it is possible to determine differences in the short circuiting timing.

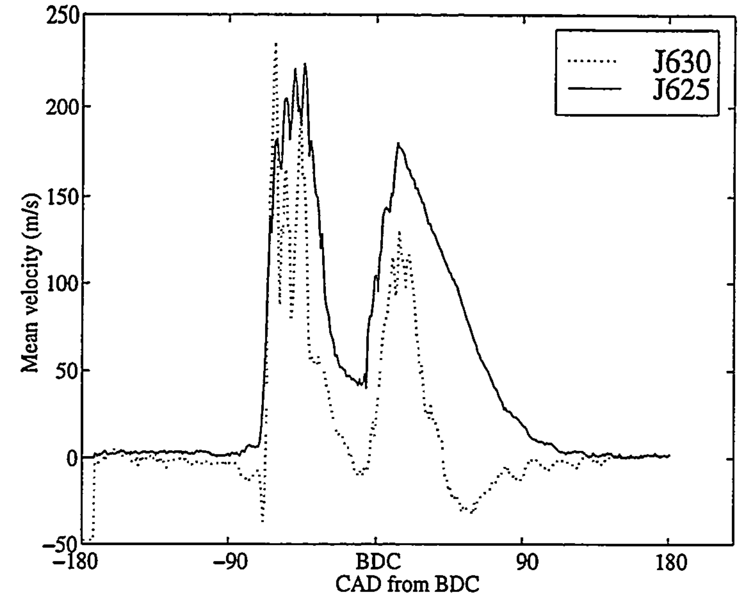

***Figure 28** Mean velocity outside the exhaust port of both J625 and J630 (open and cup handle transfer channels respectively) [3].*

Figure 28 shows the mean velocity outside the exhaust port for both cylinder types. It can be noted that the timing of the exhaust pulse seems to be the same for the two geometries. However, the last velocity peak is considerably higher for the cylinder with open transfer channels. If it is believed that the first velocity peak is burned gas and that the second is short-circuited fuel, which seems believable, the short-circuiting velocity is higher for the cylinder with open transfer channels, a theory supported by the fact that the cylinder with open transfer channels short-circuit more of the fuel than the other cylinder design.

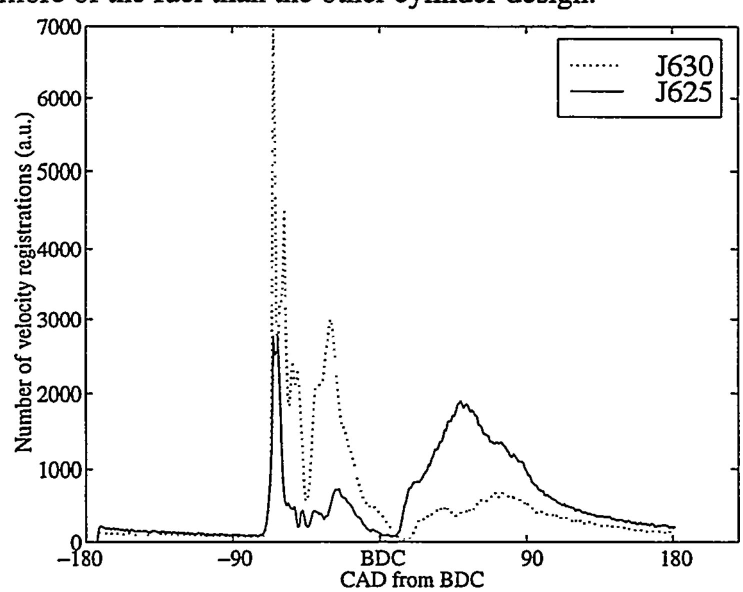

***Figure 29** Data rate for LDV measurements performed outside the exhaust port, indicating the flux of naturally occurring particles [3].*

Figure 29 show the data rate outside the exhaust port. The data rate is a rough way to estimate the particle density in the flow, and as can be seen, the particle density late in the scavenging phase is higher for the cylinder with open transfer channels than for the cup handle cylinder. This emphasises the theory from the pure velocity measurements that the short-circuiting is higher for the open transfer channels.

5.3.2.4 LIF outside the exhaust port

The results from the LIF measurements confirm the conclusions that was drawn from the results from the LDV measurements outside the exhaust port. The short-circuited part of the total hydrocarbon emission is larger for the cylinder with open transfer channels. Furthermore, it can be concluded that the short-circuiting starts earlier in the cylinder with open transfer channels. For the cylinder with cup handle transfer channels, the short-circuiting starts after BDC and continues until the exhaust port closes. For the cylinder with open channels, the short-circuiting seems (for the LIF measurements) to commence almost as soon as the scavenging starts.

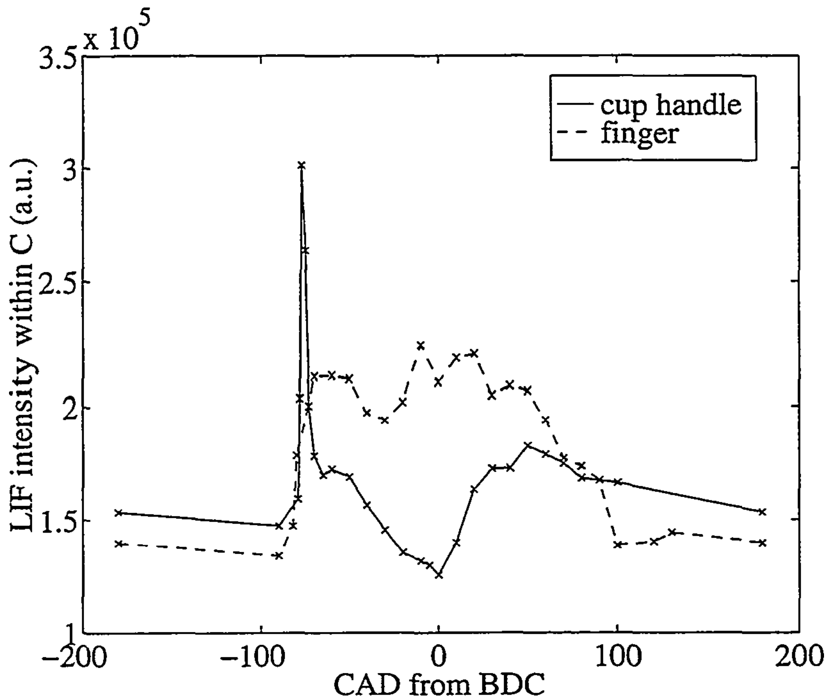

Figure 30. LIF signal mainly from the fuel tracer 3-pentanone in the exhausts. It can be noted that the signal is very low around BDC for the cylinder with cup handle channels around BDC. For the cylinder with open transfer channels (a.k.a. finger channels), the signal is more evenly distributed [3].

The differences between the LDV measurements and the LIF measurements probably come from the different emission phases. Parts of the exhausts are in gas phase, some in liquid phase and, probably a minor part, in solid phase. The LDV measurements are only able to detect the liquid and the solid phase of the fuel. LIF can detect both the liquid and gas phases of 3-pentanone, although not with the same signal strength.

The LIF measurements presented in this thesis suffer from one other disturbing phenomenon; the lubricating oil fluoresces at roughly the same wavelength as the fuel dopant. This problem is solvable, but the remaining signal suffers from low signal-to-noise ratio. .

It would be nice to make an estimate of which measurement method is the best one, but as they measure different phenomena, that is beyond the author's capability.

5.3.2.5 Laser Sheet

The results from the laser sheet measurements show that the measurements in the cylinders with cup handle transfer channels can be used to get information on the earlier part of the scavenging process, but for the open transfer channels and the later scavenging phase, the fuel droplets that are supposed to give the signal have vaporised. Therefor, the short-circuited fresh mixture can not be detected. The reason that it was possible to perform LDV measurements in this region of the cylinder is probably the droplet size; LDV can measure very small particles. The LSDI measurements is relying on signal from droplets of all sizes, and if the fuel droplets are partly vaporised (as we assume), the remaining droplets are far too small to give the required signal strength. Figures 31 and 32 show laser sheet images captured in the cylinders with open and cup handle transfer channels respectively.

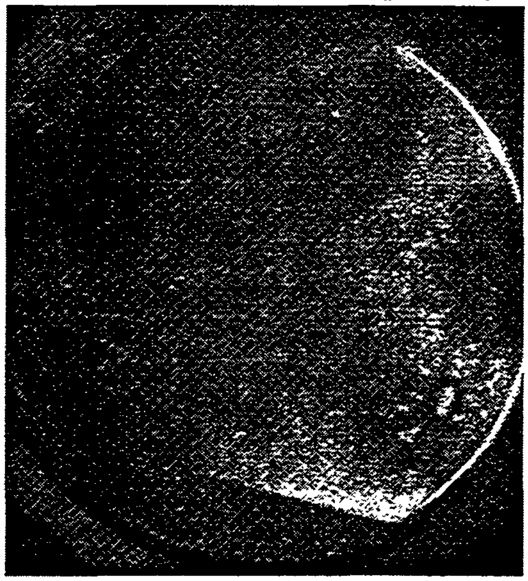

***Figure 31** The droplet concentration pattern in the J625 cylinder (open transfer channels) at Bottom Dead Centre. Note that the concentration seems to be lower close to the exhaust port. The LDV measurements show no flow that supports this difference in concentration pattern [13].*

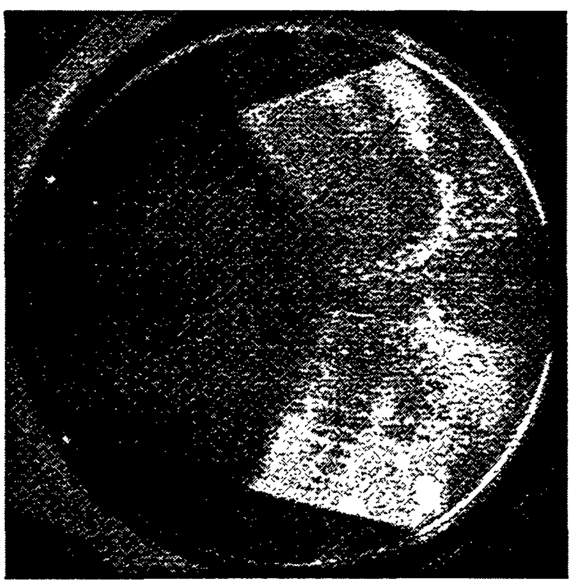

***Figure 32** The droplet concentration pattern in the J630 cylinder (cup handle transfer channels). The angle out from the transfer channels seems to agree well with the result from the LDV measurements [13].*

5.3.3 Comparisons and discussion

Presented results show that the flow behaviour in the J625 (open transfer channels) cylinder is inferior to the flow in the cylinder J630, and other cylinders with cup handle transfer channels.

- The LDV measurements through the exhaust port gives the horizontal and the vertical flow velocities. Since the measurements were performed in three different planes, it could be deduced that the loop-scavenging effect was poor for the cylinder with open transfer channels and much more beneficial for the other ones.
- The LDV measurements performed through the cylinder head show that the flow in the cup handle transfer channel agree fairly well to the design angles for the transfer channels. This is not the case for the cylinder with open transfer channels.
- The velocity measurements outside the exhaust port does not tell anything about the in cylinder flow behaviour, but do however tell something about the timing of the short-circuiting: The cylinder with open transfer starts short-circuiting of the load earlier than the cylinder with cup handle transfer channels.
- The LIF measurements outside the exhaust port allowed more certain conclusions to be drawn about the content in the exhaust gases. The LIF measurements proved that the assumption from the LDV measurements, that the content in the exhaust gases late in the scavenging phase consisted of short-circuited gas, was right.
- The laser sheet images suffered from the vaporisation of the fuel that occurred close to the exhaust port. This made it impossible to draw more than one conclusion from the laser sheet measurements: the technique can be used to measure the angle out from the transfer channels, if the transfer channels are of the cup handle design.
- The difference between the laser sheet images, in which it was impossible to get any signal from the burned gases and the LDV measurements outside the exhaust port, where signal from the exhaust gases was obtainable, is probably explained by the different demands on particle sizes for the different measuring techniques. LDV can use very small particles to perform measurements. LSDI on the other hand can use both very small and very large particles to get the signal. The smaller particles give a very weak signal compared to the large one. Thus it can be assumed that the particles in the burned gases are significantly smaller than in the fresh mixture.

5.4 Scavenging timing and dynamic effects

If the pressure in the cylinder exceeds the pressure in the crankcase as the scavenge port opens, the scavenging of the cylinder will be delayed until the pressure in the cylinder has dropped below the pressure in the crankcase.

The amount of short-circuited fuel and the output power can differ substantially for two-stroke engines with different port timings. This variation is mainly originating from the differences in scavenging timing for the different port heights; a high and wide exhaust port lets a larger part of the exhaust pressure out from the cylinder before the transfer channels open than a low, narrow one does. This is the reason why high speed two-stroke engines generally have a larger distance between the exhaust opening and the transfer channel opening than engines designed for low engine speeds.

The scavenging delay can only be measured in a fired engine run at the rated speed for the following reasons:

- In motored engines, the pressure in the cylinder is lower rather than higher than atmospheric pressure as the exhaust port opens since heat losses to the cylinder walls reduces pressure somewhat. This means there is no scavenging delay in a motored engine.

- In a fired engine, there is a substantial density difference between the burned gases and the fresh gases. This <u>can</u> be achieved for the <u>first</u> revolution in a motored engine, by using air in the cylinder and carbon dioxide in the crankcase ("single cycle test") [4].
- At low engine speed, there is enough time to let the pressure in the cylinder out through the exhaust port before the scavenging ports open.

The dynamic effects in the engine is substantially different in a motored engine at low engine speed from a fired engine at high engine speed.

5.4.1 LDV through exhaust port

The LDV measurements through the exhaust port showed that the scavenging delay was about 30 degrees. When looking on the velocity as a function of CAD in figure 33, it can be seen that the flow velocity out from the transfer channels seems to peak twice during the scavenging: Just as the fresh mixture starts to flow into the cylinder and at about 30 CAD:s after BDC.

The data rate as a function of CAD shown in figure 34, shows that the data rate distribution is very uneven over the scavenging phase. The large fluctuations do not necessarily depend on concentration differences, but can as well be an artefact of refractive index gradients in the cylinder, that can disturb the laser beam intersection during fractions of the scavenging phase. The drop in data rate at 5 CAD:s before BDC is most likely a result from such a gradient.

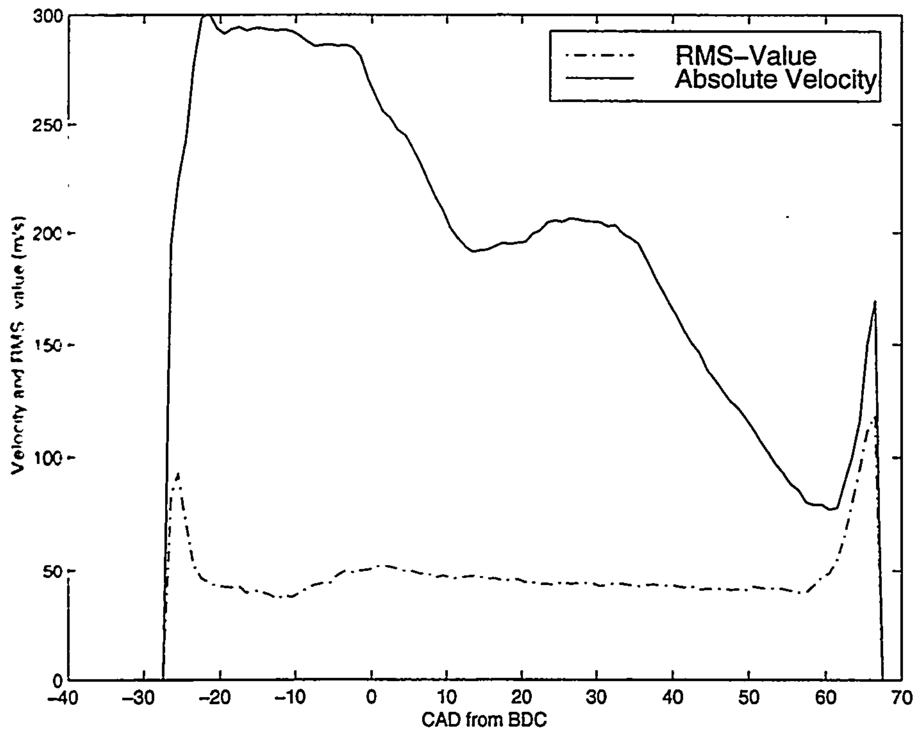

Figure 33 The absolute velocity and the absolute turbulence measured just outside the transfer port on the J625 engine at the height of 7 mm over the piston top at Bottom Dead Center, BDC, as a function of CAD (Crank Angle Degree) [10].

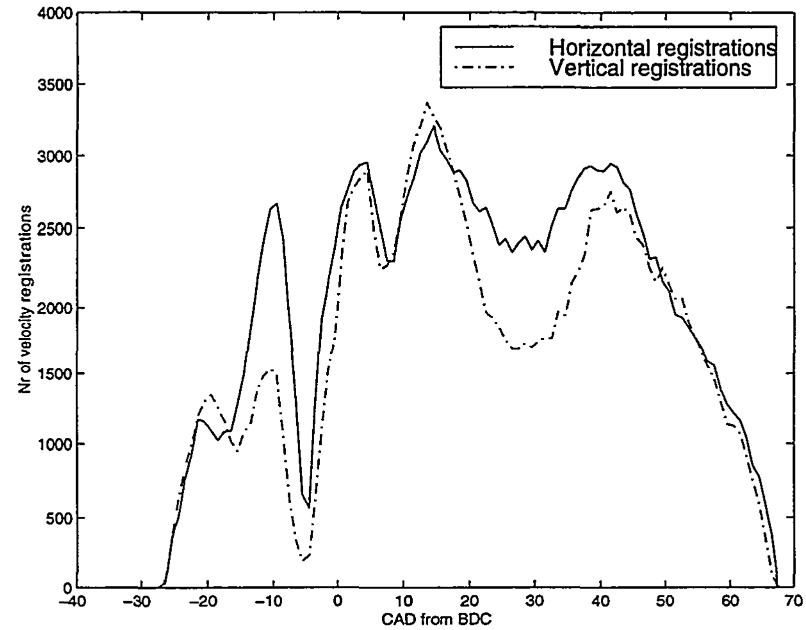

Figure 34 The number of velocity registrations as a function of CAD. This measurement was performed in the J625 engine just outside one transfer channel [10].

5.4.2 LDV through cylinder head

The LDV measurements with the cylinder head as the optical access way show that the scavenging delay is almost equal when measuring through the cylinder head and measuring through the exhaust port. Compare figures 33 and 35. This was rather surprising, since the measurements through the exhaust port were performed without the silencer attached. The silencer ought to give a slower pressure drop in the cylinder as the exhaust port opens, due to the increased choking of the flow, and hence give a longer scavenging delay. This was, however, not the case.

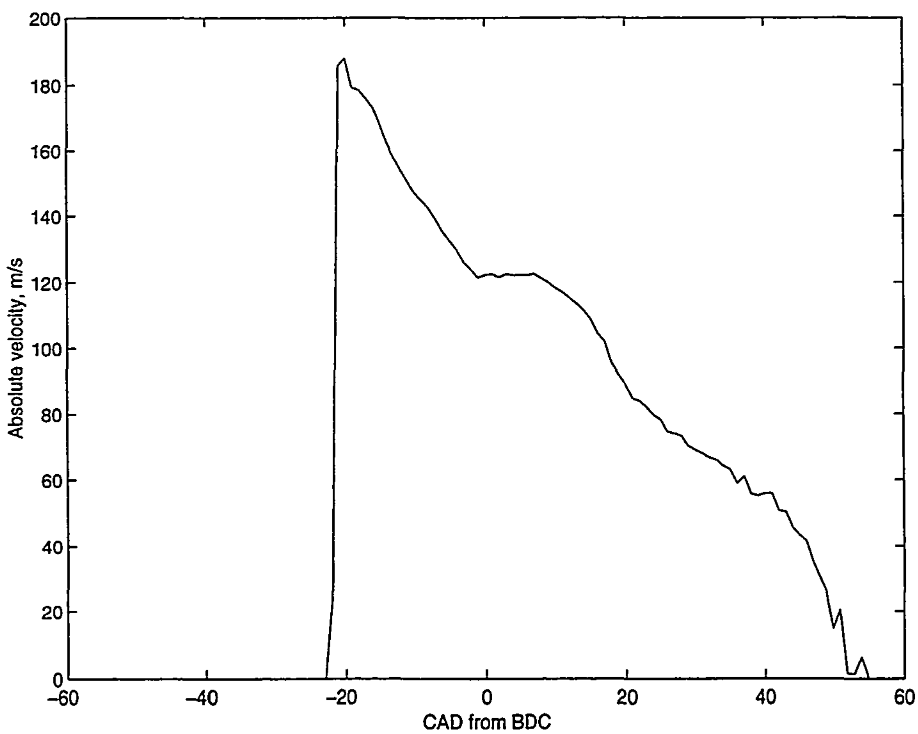

Figure 35The absolute flow velocity out from the transfer ports in the engine J625, open transfer channels. Note that the scavenging delay seems to be equal to the scavenging delay *found in the measurements through the exhaust port. The velocity is however lower, and it decreases almost linearly as the CAD increases.*

5.4.3 LDV outside the exhaust port

The LDV measurements performed outside the exhaust port show the velocity of the burned gases (the blow-down phase) and the velocity of the short-circuited mixture. As can be seen in figure 36 ,the flow velocity outside the exhaust port peaks just as the exhaust port opens (the blow-down phase), and as well in the latter part of the scavenging. It can be assumed that the first peak consists of burned gas, and the later peak is short-circuited fresh gas. This makes sense, as the J625 engine has got more short-circuiting losses than the J630 engine has got.

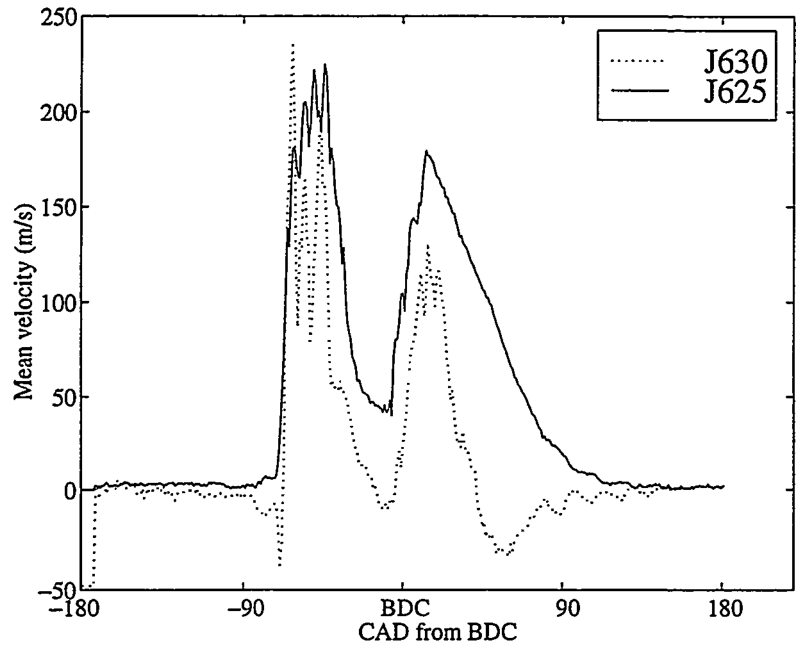

***Figure 36** The flow velocities outside the exhaust port for the two engines J625 and J630.*

The flux of particles through the measuring volume (data rate) is a very rough way to estimate the concentration of particles in the flow. In figure 37, the number of velocity registrations is plotted as a function of CAD for the two cylinder types J625 and J630. The result agrees well with other measurement methods performed outside the exhaust port, the J625 (open transfer channels) short-circuits more fresh mixture than the J630 (cup handle transfer channels) does.

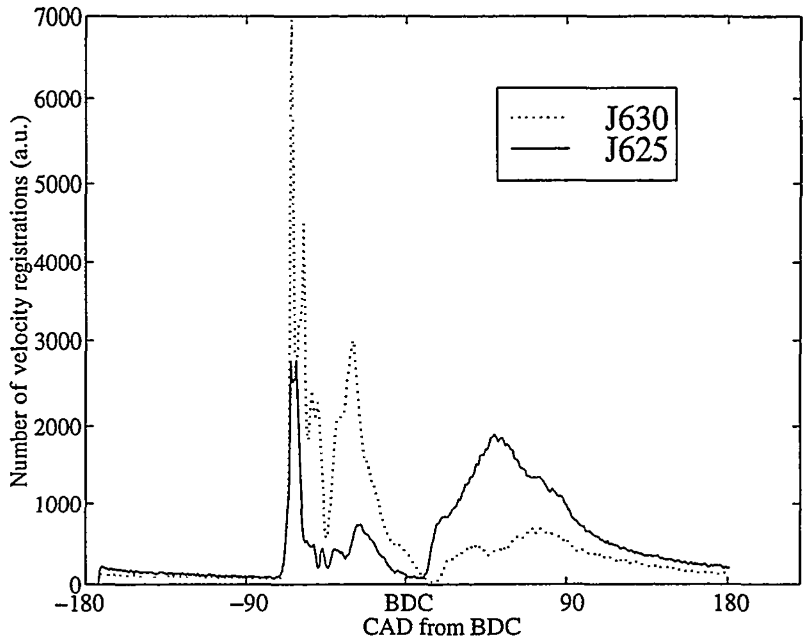

Figure 37 The number of velocity registrations as a function of CAD for the two cylinder types J630 and J625. The measurement volume was placed just outside the exhaust port.

5.4.4 LIF

The LIF (Laser Induced Fluorescence) measurements, presented in paper 961927, confirms the assumption that the short circuiting occurs during the latter part of the scavenging, and that the short-circuiting is more severe on cylinders with open transfer channels.

5.4.5 Laser Sheet

The laser sheet measurement were performed inside the cylinders, and can therefor not be compared to the LIF measurements and the LDV measurements outside the exhaust port, but they can however be compared to the LDV measurements performed inside the cylinder. In particular, it is interesting to compare the laser sheet measurements to the LDV measurements performed through the cylinder head, since these two measurement methods are measuring the same phenomena; the gas exchange.

Figure 38. *Arrows visualising the flow velocities from the transfer ports(measured with LDV) placed in the same figure as a Laser Sheet Droplet Illumination image. This image was captured as the piston position was at BDC. The cylinder was the J630 cylinder (cup handle transfer channels) [12,13].*

It turns out, that the horizontal angle of the scavenging jets is obtainable from the information in the laser sheet image, for the cylinders with cup handle transfer channels. For the cylinders with open transfer channels, the angular information is not obtainable, because the fuel droplets, that are supposed to scatter the laser light, vaporise too fast close to the exhaust port.

This phenomenon also occurs for the cup handle transfer channels, but not until late in the scavenging phase. This makes it impossible to see the fuel that is short-circuited, and that is valid for both the cylinders with cup handle and open transfer channels.

5.4.6 Comparisons and discussions

There is no doubt that the LDV measurements give the most information on the scavenging of the two-stroke engine, since both the absolute velocities, the scavenging pattern and dynamic effects can be studied using only one measuring equipment. Furthermore, the RMS-value of the velocity data obtained can be calculated.

Two very important differences are present between the LDV measurements that is performed through the exhaust port and the measurements through the cylinder head: With the exhaust port as the optical access way, the silencer can not be mounted, and the perhaps most important velocity component can not be measured. Therefor, the LDV measurements with the cylinder head as the optical access way can be regarded as the most useful, however with the most complicated experimental set-up.

The data rate can be used to estimate the concentration of particles in the flow. The drawback with the LDV measurements is that they are very time consuming

The LIF measurements outside the exhaust port can be used to deduce the amount of short-circuited gaseous fuel and the timing of the short-circuiting. It does not, however, say anything about the phenomena that causes the short-circuiting.

6 Discussion

6.1 Sensitivity analysis

6.1.1 Effects of optical access

All ways of getting optical access to the interior volumes of a combustion engine cause more or less severe differences in engine operation. In general, it can be said that the better the optical access, the more the engine operation will be affected. The two-stroke engine is generally more simple to make optically accessible than the four-stroke engine, because the lack of valves in the cylinder head, but the most simple way to get optical access is to remove the silencer and use the exhaust port as the optical access way.

6.1.1.1 Silencer removal

The LDV measurements performed through the exhaust port require, as mentioned, that the engine is run without silencer. Naturally, the lack of a silencer affects the flow behaviour. To test the difference in flow behaviour, the AC Berema engine was run both with and without silencer when the LDV measurements were performed through the transparent cylinder head. The LDV measuring volume was placed just outside one transfer channel.

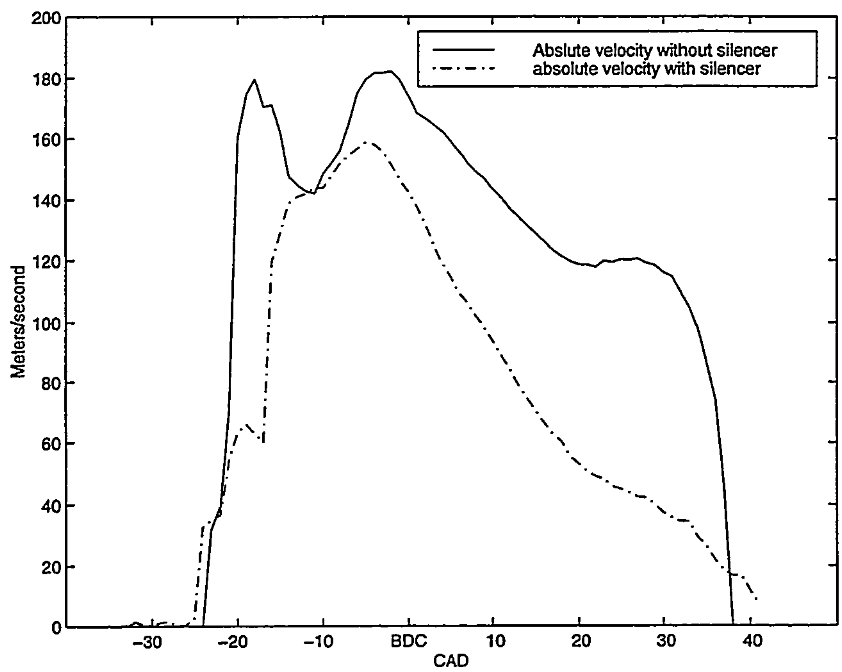

Figure 39 The difference in scavenging flow velocities just outside one transfer channel and without the silencer. Note that the scavenging delay is smaller with the silencer mounted, but the flow velocity is lower during the later part of the scavenging.

Figure 39 shows the difference in flow velocity just outside one transfer channel when the Berema engine was run with and without silencer.

The Berema engine has a significantly lower output with the silencer mounted. This can be interpreted to a high back pressure. Since the other engines show much less power drop with the silencer mounted, it can be assumed that the impact from the silencer is more severe on the Berema engine. The relatively small differences on the flow velocities with and without silencer for the Berema engine indicates that the effect on the other engines are even less severe.

6.1.1.2 Combustion chamber

The combustion chamber shape gets of course very different when the original, almost semi-hemispheric, cylinder head with a central spark plug location is replaced with a flat cylinder head with two spark plugs in the cylinder walls.

The main differences with the flat cylinder head, compared to the original, are the combustion rate, that affects the scavenging timing due to the higher pressure in the blow-down phase that will result if the combustion is slower and the different flow behaviour that will occur as the scavenging loop hits the cylinder head and is reflected down towards the exhaust port. The effect on the early part of the scavenging pattern, however, ought to be negligible.

6.1.2 Comparisons between results measured through optical cylinder head and exhaust port

The LDV measurements performed through the exhaust port and through the cylinder head differ in two important aspects; the measuring volume is larger with the access way through the exhaust port due to the necessary back scattering collection mode and the silencer not present as the exhaust port is used as the access way.

The effect of these differences is shown in this chapter.

6.1.2.1 Mean velocity

The velocity plots in figures 40 and 41 show the different flow behaviours when measuring through the exhaust port and through the cylinder head for the two cylinder types J625 and J630 (open and cup handle transfer channels respectively). The plotted flow component is the one that is directed from one transfer channels towards the other one, and parallel to the piston. The differences in mean velocity when the two different access ways are used can be explained by (at least) three phenomena:

- The silencer is not present as the exhaust port is used as the optical access way. In chapter 6.1.1.1, the effect of the silencer for the Berema engine is shown. For the Husqvarna engines, the effect of the silencer should be smaller, but is probably not entirely negligible.
- The measuring volume is larger for the measurements through the exhaust port. This makes the effect of so called gradient broadening larger for the measurements through the exhaust port.
- The cylinder individuals were different for the measurements through the exhaust port and for the measurements through the cylinder head. This is probably the reason for the very differing velocity plots for the J625 cylinder (open transfer cahnnels), shown in figure 41.

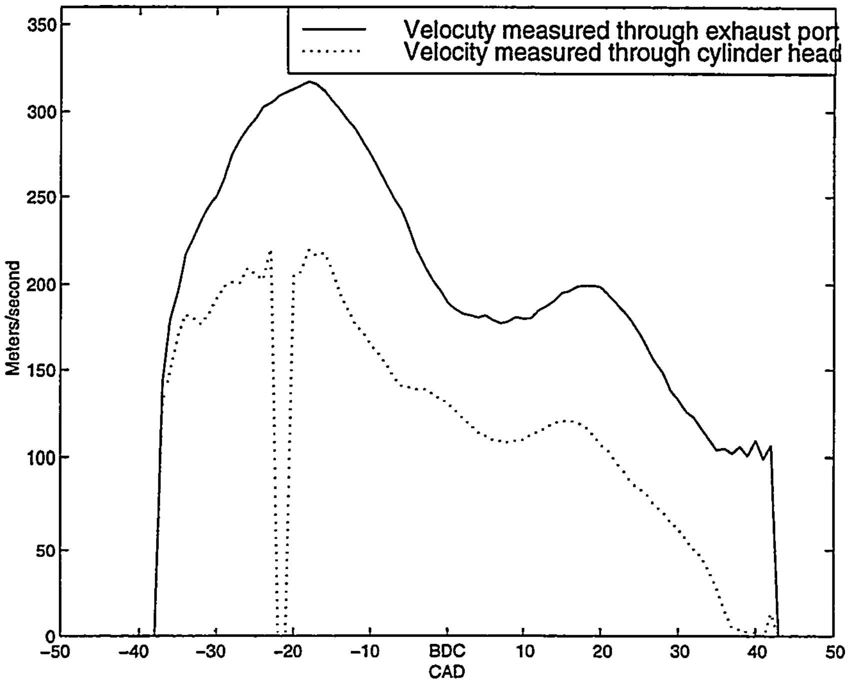

Figure 40 The difference in flow velocities for the J630 engine, when measured through the exhaust port and the cylinder head. The measuring point shown here is 10 mm's inside the centre of the cylinder (away from exhaust port) and 10 mm's to the left.

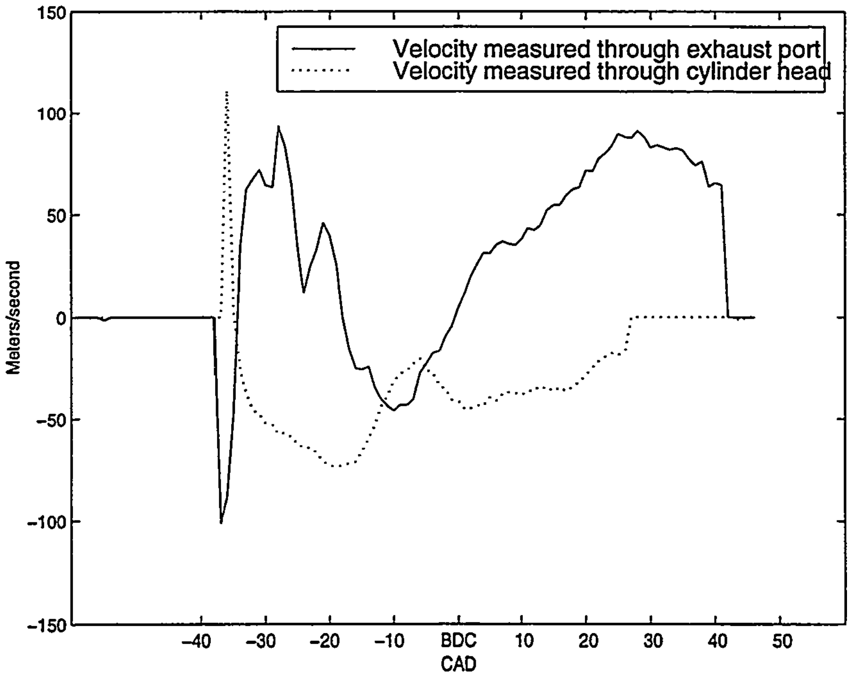

Figure 41 The difference in flow velocities for the J625 engine, when measured through the exhaust port and the cylinder head. The measuring point shown here is 10 mm's inside the centre of the cylinder (away from exhaust port) and 10 mm's to the left.

6.1.2.2 Turbulence

The reasons for the differences in turbulence levels are the same as for the differences in mean velocity (see previous chapter). It can be noted in the following figures that the turbulence level (RMS value) is significantly lower for the cylinder with cup handle transfer channels. The "dip" in turbulence level occurring at about -25 CAD's for the LDV measurements performed through the cylinder head in the J630 engine (cup handle channels), is probably due to some kind of shock wave that passes the measuring volume at that time. In a shock wave, the refractive index of the gas changes, and hence there will be no overlap of the emitting and collecting measuring volumes (see chapter 4.2.2.2) and hence no velocity data and hence no RMS value. It can as well be seen in the previous chapter that there is no velocity data around -25 CAD's from BDC.

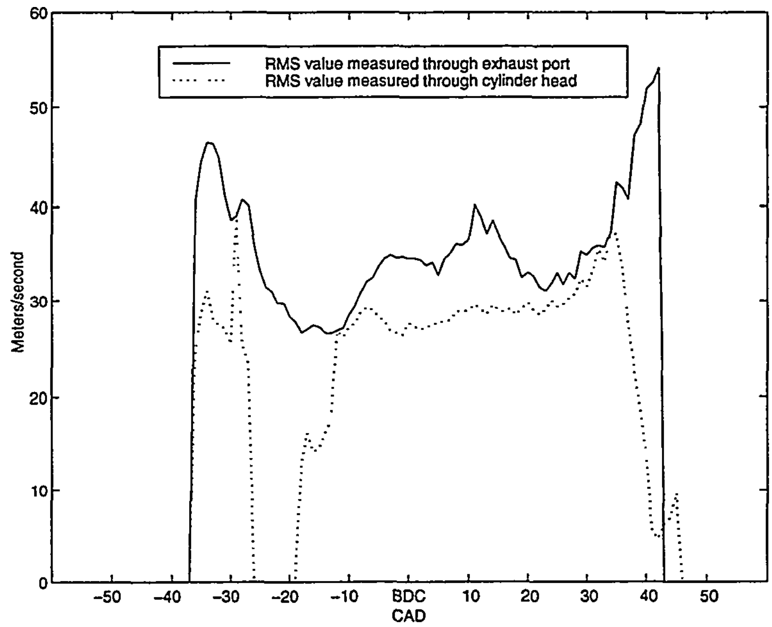

Figure 42 The difference in RMS value (turbulence) for the LDV measurements performed through the exhaust port vs. the LDV measurements performed through the cylinder head in the J630 engine (cup handle transfer channels).

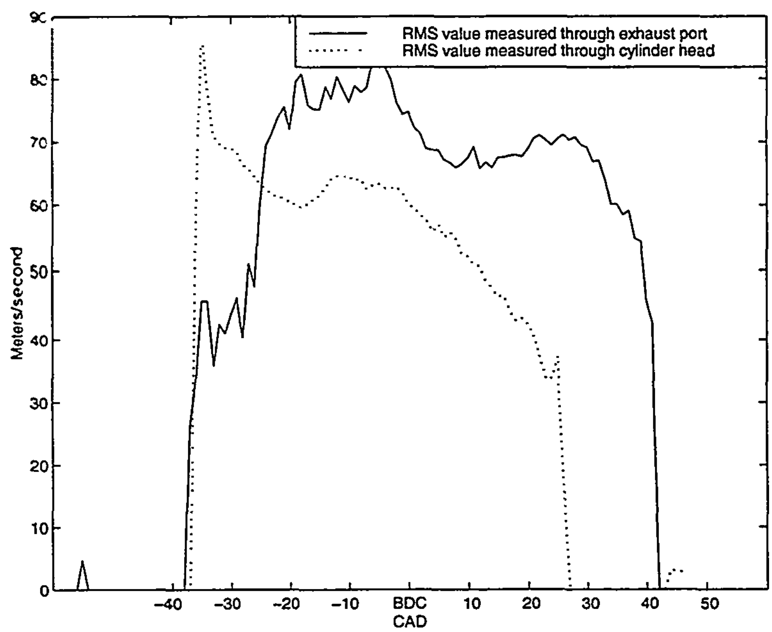

Figure 43 The difference in RMS value (turbulence) for the LDV measurements performed through the exhaust port vs. the LDV measurements performed through the cylinder head in the J625 engine (open transfer channels). The reason why the registrations for the LDV measurements through the cylinder head stop earlier is that the measuring volume hits the piston top earlier than it was supposed to (wrong measuring height).

6.1.3 Differences between cylinder individuals

During the experimental work, quite a few different cylinder individuals of each type were examined. Those different cylinder individuals show some differences in the flow behaviour (such as slightly different scavenging jet angles).

The reason that several different cylinder individuals were used was that the cylinders occasionally seized, and therefor were rendered useless for further investigations. Since the measurement series most often were not fulfilled for a cylinder that seized, no further investigations were performed to analyse the reasons for the individual differences.

The explanation to the differences for the cylinder individuals is probably the method used to manufacture the transfer channels: The cylinder is cast, and it is less expensive to use a mould that leaves a space for the transfer channels in the cylinder walls than to machine the transfer channel after the cylinder is cast. The less expensive method of casting the transfer channels gives however a lower degree of accuracy in the transfer channel design.

6.2 Possible improvements on the scavenging of two-stroke engines

The scavenging of two-stroke engines is a very complicated process, and many efforts have been made during the years to develop a better scavenging pattern. There are methods that can improve the scavenging substantially, i.e. use a uniflow scavenging arrangement. Although, one must not forget the advantages with the small two-stroke engines as they are designed today; they are uncomplicated, have got a high power to weight ratio and can be manufactured at a low cost. Adding a uniflow scavenging to such a small engine would substantially increase the costs and add to the complexity of the engine.

The simple loop-scavenging has undergone thorough investigations, not a small part of its development has been performed in racing applications, where the high power to weight ratio of the two-stroke engine is very useful. By time, experience has led to some very useful design rules, concerning the angles at which the scavenging jet shall enter the cylinder, to give an as good scavenging as possible. Professor Blair's two books on two-stroke engines can be a good help to an engine designer [4,5].

The Author's very personal opinion is that there is not very much more to be done in terms of reducing the short-circuiting losses from small two-strokes by changes of the transfer channel designs.

For the last years, direct injection technology has been "among the hottest" in the engine research world. On four stroke engines, the direct injection can improve the fuel economy by some percents, to the price of a more polluting engine. On two-stroke engines, both the emission level and the fuel economy are improved significantly. The two-stroke engine's major emissions emanates from the short-circuiting of fuel. With a direct injection system, the short circuited gases consist of pure air, and hence the HC emissions are reduced [1, 27, 29].

Another major advantage with using a direct injection system is that the weight of the engine does not increase significantly, and the power to weight ratio can be kept high.

7 Summary

Four different engines with different transfer channels have undergone a thorough investigation with different laser techniques:

- LDV through the exhaust port, on different positions inside the cylinder.
- LDV through the cylinder head.
- LDV outside the exhaust port.
- LIF outside the exhaust port.
- Laser Sheet Droplet Illumination inside the cylinder.

All measurement were performed in engines running at their rated speed (9000 rpm for three of the engines, 5800 for one of them). The engines were fired, run at full load.

The different measurement methods enabled the following conclusions:

- LDV through the exhaust port showed that the loop-scavenging effect was poor in the cylinder with open transfer channels, but much better with the cup handle transfer channels.
- The LDV measurements through the cylinder head showed the reason for the poor loop-scavenging in the cylinder with open transfer channels; the jets that scavenges the cylinder has got no measurable velocity component towards the back wall of the cylinder, but instead just meet in the centre of the cylinder. The cylinders with cup handle transfer channels, on the other hand, have a significant velocity component towards the back wall of the cylinder. This results in a much more loop-like scavenging, and as a result, the short-circuiting level is significantly lower on these cylinders.
- The LIF measurements performed outside the exhaust port showed that the timing of the short-circuiting was different for the cylinder with open transfer channels compared to the cylinders with cup handle transfer channels; the open transfer channelled cylinder short-circuits fuel during almost the entire exhaust period, whereas the cylinder with cup handle transfer channels short-circuits the fuel only later in the exhaust period.
- The LDV measurements outside the exhaust port show the same phenomena as the LIF measurements do; the short-circuiting occurs later in the cylinder with cup handle transfer channel. The main difference between the two measurement methods is that the LDV measurements do not give any information on the contents of the exhausted gases, but only how much particles there is in the gas. Combined with the LIF measurements, it can however be concluded that the peaks in velocity data rate emanate from short-circuited fuel.
- The Laser Sheet Droplet Illumination images showed as well the difference between the two cylinder types, although not as visible as the LDV measurements through the top did. The reason for the less precise results from the laser sheet measurements was that the fuel droplets vaporised close to the exhaust port, and where a mixing between the scavenging jets and the exhaust gases occurred.

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