MASTER

Measurements on a multiple pulsed plasma torch in an atmospheric environment

van Raay, L.J.H

Award date:
2006

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
Measurements on a multiple pulsed plasma torch in an atmospheric environment

By: L.J.H. van Raay
EPS.06.A.178

Supervisors:

prof. dr. ir. J.H. Blom
dr. ing. A.J.M. Pemen

March 2006
Summary

The multiple pulsed thermal plasma torch is a concept with a promising outlook into chemical applications, including nano-particle production, gas cleaning and biological treatments. Pulsed power technology has the advantage of being able to control the process in the pulsed plasma reactor. Alteration of pulse length and pulse amplitude could lead to different thermal effects. Synchronizing multiple torches provides a well controlled distribution of the plasma in space and time. To improve the knowledge about the pulsed thermal plasma torch, measurements on a scale model are required.

The pulsed thermal plasma torch proposed by Eindhoven University of Technology was investigated by the author of this report. The research focussed on the formation of the high-voltage pulse and the effect of different pulse shapes on the pulsed thermal plasma. A simple pulsed thermal plasma current model was proposed and verified by measurements. The model provides a technique to estimate the pulse shape of the current.

Different pulse shapes were investigated by measuring the energy balance. The pulsed thermal plasma torch converts about 60%-70% of the electrical energy into heat absorbed by the surrounding air. The different pulse shapes showed no significant differences in the energy balance. The basic plasma diagnostics could play a role in this case. More advanced plasma diagnostics could gain insight into the physical differences between several pulse shapes.

The multiple pulsed thermal plasma torch was investigated with respect to the energy distribution among the several torches. To ensure a homogenous energy distribution, two techniques are proposed; series inductors and a choking coil. Investigation on these two techniques was performed. While both techniques could provide the desired result, the series inductors seem to have more practical limitations.

The results of this research will be submitted to the 6th International Symposium on Pulsed Power and Plasma Applications, Chengdu, Sichuan, China, 18-22 September 2006.
# Contents

## Summary

### 1 Introduction
1.1 Project description ........................................ 1
1.2 Objectives ............................................... 2
1.3 Outline .................................................. 2

### 2 Circuit topology
2.1 Circuit analysis .......................................... 5
2.2 Transient and thermal mode .............................. 5
  2.2.1 Transient mode ...................................... 6
  2.2.2 Thermal mode ...................................... 6
2.3 Trigger circuit .......................................... 7
2.4 Multiple pulsed plasma torch ............................ 7
  2.4.1 Multiple torch circuit analysis .................... 7
  2.4.2 Thermal mode complication ......................... 8
2.5 Pulsed thermal plasma model ............................ 9
  2.5.1 Transient mode .................................... 9
  2.5.2 Thermal mode .................................... 10

### 3 Plasma torch
3.1 Plasma torch design ...................................... 11
  3.1.1 Construction ....................................... 11
  3.1.2 Gas flow ......................................... 12
  3.1.3 Trigger pin ....................................... 13
3.2 Design considerations .................................. 14
  3.2.1 Triple points .................................... 14
  3.2.2 Electrode configuration ............................ 14

### 4 Measurement techniques
4.1 High voltage measurements .............................. 15
4.2 Current measurements .................................. 16
4.3 Data recording .......................................... 16
4.4 Power and energy calculations .......................... 17
  4.4.1 Averaging ........................................ 17
  4.4.2 Transient and thermal mode ....................... 18
4.5 Temperature measurement .............................. 18
CONTENTS

4.6 Plasma diagnostics ............................................. 18
4.6.1 Heat production ........................................... 18

5 Measurement results ............................................. 21
5.1 Typical waveforms ............................................ 21
5.2 Stability ..................................................... 23
5.3 Model validation .............................................. 24
5.3.1 Transient mode ........................................... 25
5.3.2 Thermal mode ........................................... 25
5.4 Configurations ............................................... 26
5.4.1 Plasma diagnostics ....................................... 26
5.4.2 Energy per pulse ......................................... 28
5.4.3 Stability .................................................. 29
5.4.4 Pulse length ............................................. 29
5.4.5 Current thermal mode ................................... 30
5.5 Multiple torches ............................................. 30
5.5.1 Series inductors .......................................... 31
5.5.2 Choking coil ............................................... 32
5.5.3 Conclusion ................................................ 33

6 Conclusions and recommendations .............................. 35
6.1 Conclusions .................................................. 35
6.2 Recommendations ............................................. 35

Bibliography ....................................................... 38

List of Figures ....................................................... 40

List of Symbols ..................................................... 41

Acknowledgements .................................................. 43

A Multiple torch complication ......................................... 45
A.1 Unstable operation .......................................... 45
A.2 Stable operation ............................................ 45
A.3 Multiple torch operation ................................... 47
A.4 Solutions .................................................... 47

B RLC circuit analysis ............................................. 49
B.1 RLC circuit ................................................... 49
B.1.1 Underdamping ............................................ 50
B.1.2 Damping coefficient ...................................... 51
B.2 RLC circuit with diode ...................................... 52
B.2.1 Reversely biased diode .................................. 53
B.2.2 Forwardly biased diode .................................. 53
C Source code
   C.1 Initialization routine ........................................ 55
   C.2 Standard measurement routine ............................... 56
   C.3 Averaging measurement routine ............................. 57
   C.4 C++ measurement routine ................................... 59
   C.5 Matlab compression routine ................................ 68
   C.6 Pulsed thermal plasma model ............................... 68

D Measurement data
   D.1 Heat balance .................................................. 71
       D.1.1 Configuration 1 ......................................... 71
       D.1.2 Configuration 2 ......................................... 76
       D.1.3 Configuration 3 ......................................... 81

E Abstract Symposium Pulsed Power and Plasma Applications 87
Chapter 1

Introduction

1.1 Project description

Plasma technology is a rapidly evolving technology with a broad application potential. Today, plasmas find a wide range of applications, including thin film deposition, plasma chemistry, materials synthesis and environmental applications [Bon02][Pfe99].

Thermal plasmas or equilibrium plasmas are characterized by high temperatures and high currents. High temperature processes such as incineration processes, layer deposition and nanoparticle production are possible with the use of thermal plasmas. Thermal plasmas are usually generated by DC transferred, DC non-transferred arcs or RF inductively coupled plasmas [Con00][Fau97].

Because of the continuous operation of these plasma generation types, the power of the plasma will also be continuous, while optimal processing conditions may require otherwise. Furthermore, thermal plasmas require high currents to sustain the plasma. The electric power a thermal plasma dissipates is therefore high. Improving the efficiency of a process inside a thermal plasma reactor is needed to make plasma technology profitable for the industry.

Pulsed plasmas can overcome this issue because of the discontinuous property. Variables that are not applicable to continuous plasmas, such as the pulse length, give new possibilities of controlling the process inside a pulsed plasma reactor. These extra parameters could optimize the conditions for various processes. Applications of interest would be thin film deposition, plasma chemistry and materials synthesis.

In the case of thin film deposition, the need of the industry is to speed up the deposition process, which would lower the costs of the product. Non-continuous operation of a thermal plasma torch can enhance the deposition process [Bie02].

Plasma chemistry, such as waste incineration, provides more environmentally friendly techniques than conventional incineration can [Ram02][Yao01][Wal00][Ben97][Fau97][Man97]. In the case of thermal plasma waste incineration, organic material can be converted to synthesis gas, while inorganic material can be converted to construction material. However, electricity is usually more expensive than natural gas. Improving the efficiency of thermal plasma waste incineration could make this technique profitable.

Physical properties of materials change as their size approaches to nanoscale. Nanoparticles are therefore of great scientific interest. Nanoparticles and nanotubes offer new possibilities for the semiconductor industry and provide extraordinary material properties, such as extreme tensile strength and high flexibility. Materials synthesis, more specifically nanoparticle synthesis, is possible inside a thermal plasma reactor [Har04][Kim01][Bil97]. Again, an efficiency optimization is crucial to make these
products profitable for the industry. Eindhoven University of Technology introduced a novel concept to drive a pulsed thermal plasma reactor [Hee03]. This concept is innovative, not only because of the non-continuous operation of the thermal plasma torch, but also for the different modes it introduces. As will be explained later on in this report, the two different modes consist of a transient mode and a thermal mode. The transient mode is characterized by high currents and a short duration. The thermal mode has a longer duration and the typical current is lower. Parameters of these two modes, such as duration and peak amplitude, can be adjusted in a straightforward manner. This provides an easy pulse adaptation. This pulse adaption could even take place when the pulsed thermal plasma torch is in operation. The concept introduced by Eindhoven University of Technology introduces new parameters to control a pulsed thermal plasma torch. However, the relevance of these parameters for process optimization purposes has not been established. To gain more insight in the effect of the pulse shape parameters, research is necessary.

1.2 Objectives

The pulse shape that drives the pulsed thermal plasma torch can be adjusted. Suppose the pulse shape parameters to optimize a particular process are known. The pulsed thermal plasma torch should be driven by this pulse. Research should clarify how the pulse shape can be adjusted to given parameters. The transient mode and the thermal mode of the pulsed thermal plasma torch offer two different regimes in which the pulsed thermal plasma torch can operate. Differences between these two modes are expected, but not yet proven. Research in this area should gain insight in these differences. To provide a higher plasma volume, multiple torches can be connected to a single pulse source. Synchronization of the pulsed thermal plasma torch is important, because the process inside one torch should be identical to the process in every other torch. For the same reason, the energy distribution among the several torches should be homogenous. To investigate the synchronization and the energy distribution, research is necessary.

1.3 Outline

This report describes the research that was performed on the pulsed thermal plasma torch. The project was carried out by the author of this report as his Masters of Science graduation project. Chapter 2 describes the circuit that is contrived by the Eindhoven University of Technology. The chapter deals with the explaining of the circuit. Furthermore, a pulsed thermal plasma model is introduced in this chapter. The construction of the plasma torch is described in chapter 3. Some improvements on a future pulsed thermal plasma torch are suggested. Measurement techniques used in this research are described in chapter 4. Equations that convert measurement data to the quantity of interest are also presented in this chapter. The results of the measurements are discussed in chapter 5. Conclusions and recommendations can be found in chapter 6. Derivations and explanation of the pulsed thermal plasma model are included as appendix B. Appendix C lists the source code that was used to retrieve measurement data. Source code that was used to analyze the data is also included. The measurement data of the energy balance of the pulsed thermal plasma torch is included as appendix D.
The abstract submitted to the 6th International Symposium on Pulsed Power and Plasma Applications is included as appendix E.
Chapter 2

Circuit topology

2.1 Circuit analysis

The basic circuit of the pulse source is shown in figure 2.1. Numerous trigger circuits, snubber circuits, freewheeling diodes and safety circuits are present in the actual pulse source. Since these circuits are not relevant to the understanding of the operation of the pulse source, these components are omitted.

![Figure 2.1: Pulsed plasma torch circuit](image)

The pulse source is fed via a three phase mains supply. The buffer capacitor $C_0$ is charged via a diode rectifying bridge. When thyristor $T_1$ fires, the low voltage capacitor $C_L$ is resonantly charged via inductor $L_1$. At the end of this charging cycle, the current through $C_0 - L_1 - C_L$ becomes zero and $T_1$ opens. Now, when thyristor $T_2$ fires, the pulse transformer $TR$ multiplies the voltage by a factor 30. The thesis [Yan01] provides a more detailed description of the pulse source.

The high voltage capacitors $C_{th}$, $C_{tr}$ and the transmission line $TL$ are charged after $T_2$ fires. The voltage over the coil $L_1$ remains low, since the current through the coil will remain low until the torch gap breaks down. Since $C_{th}$ and $C_{tr}$ are charged, the voltage will increase over these capacitors. The voltage over the torch will increase at the same rate until the torch breaks down. After the breakdown has occurred, the voltage over the torch will drop significantly.

2.2 Transient and thermal mode

The following section describes the two different modes of the pulsed thermal plasma torch. Consider the high voltage part of the circuit shown in figure 2.1, where the capacitors $C_{th}$, $C_{tr}$ and the
transmission line have the initial voltage $V_0$ and the torch breaks down. This situation is depicted in figure 2.2.

![Figure 2.2: High voltage part](image)

Figure 2.2: High voltage part

![Schematic waveforms](image)

(a) Schematic voltage waveform  
(b) Schematic current waveform

Figure 2.3: Schematic waveforms

2.2.1 Transient mode

After a breakdown has occurred, the two high voltage capacitors, $C_{th}$ and $C_{tr}$, and the energy in the transmission line TL will discharge into the plasma. Because of the inductor $L_5$ with a high inductance, the high voltage capacitor $C_{th}$ cannot discharge immediately into the plasma, in contrast to high voltage capacitor $C_{tr}$. High voltage capacitor $C_{tr}$ will discharge via the transmission line TL after a breakdown has occurred. The result hereof is a high amplitude, fast oscillating current through the torch plasma. The frequency of this oscillation is determined by the value of capacitor $C_{tr}$ and the specifications and the length of the transmission line TL. This oscillation will be regarded as the transient mode of the plasma torch.

2.2.2 Thermal mode

As previously stated, the capacitor $C_{th}$ is obstructed with an inductor, $L_5$, which prevents immediate discharge of the capacitor. The diode $D_2$ prevents the inductor $L_5$ and the capacitor $C_{th}$ to form an oscillating LC circuit, while this is not the case in the transient mode.

At first, the diode $D_2$ is reversely biased. The capacitor $C_{th}$ discharges into the inductance $L_5$, the voltage over the capacitor $C_{th}$ will therefore decrease. Once the voltage over the capacitor $C_{th}$ drops below the threshold voltage of diode $D_2$, the diode will start to conduct. The energy in the inductor will then discharge slowly into the plasma via the diode $D_2$. The current through capacitor $C_{th}$ is therefore eliminated, thus no oscillation is expected from this point onwards. This slower mode will be regarded as the thermal mode of the plasma torch.
2.3 Trigger circuit

Triggering provides a stable breakdown voltage, this means that the energy per pulse will be more stable from pulse to pulse. This will result in a more precise determination of power input of the plasma torch. The triggering circuit used to trigger the plasma torch is shown in figure 2.4. The switch in the circuit is a fast high voltage thyristor switch, type HTS 120-100-SCR of the Behlke company.

![Figure 2.4: Trigger circuit](http://www.behlke.de)

The voltage source V provides a 10 kV DC voltage. When the voltage source is switched on, the capacitor C will charge. After the switch is closed, this capacitor will discharge, inducing a current through the primary winding of the transformer. The secondary winding is connected to a trigger pin and to the ground connection of the plasma torch.

The trigger pulse for the Behlke thyristor switch is provided by the control electronics of the pulse source. The moment of triggering can be adjusted by a potentiometer. The trigger pulse is transported to the Behlke thyristor switch through a glass-fibre, electrical interference is therefore eliminated.

The construction of the trigger pin is described in section 3.1.3.

2.4 Multiple pulsed plasma torch

The pulse source provides enough power to energize more pulsed thermal plasma torches. A parallel configuration would seem a logical choice, but this would not guarantee a synchronized breakthrough of the torches. A series configuration would provide a synchronous breakdown, but the energy dissipation in one spark gap would be less than in the original configuration. A middle course is presented in figure 2.5.

2.4.1 Multiple torch circuit analysis

As shown in figure 2.5, the transmission lines are connected in parallel at the pulse source side, while the plasma torches are connected in series. To provide a better understanding of this circuit, an equivalent circuit of the output of the transmission lines is needed. Suppose two plasma torches are connected as described above. The equivalent circuit of this configuration is shown in figure 2.6, where $V_o$ represents the voltage pulse which enters the transmission line. The secondary mode

1. http://www.behlke.de
impedance $Z_s$ consists of the inner conductor of one transmission line and the outer conductor of the other transmission line. This impedance depends on the length of the transmission line and, if present, the common mode choke applied to the transmission lines. This common mode choke is usually increased with Metglas or ferrite cores.

After one torch has broken down, a current will flow through one of the torches and the secondary mode impedance, $Z_s$. Since the secondary mode impedance is high ($Z_s \gg Z_0$), this current will be small. Therefore, hardly any energy is dissipated into the torch. Because of the low impedance of the conducting plasma torch, the voltage over the non-conducting plasma torch will rise since the two voltage sources are in series now. This rise in voltage ensures a breakdown of the second plasma torch. After the second breakdown, the current will increase and the current through torch 1 should coincide with the current through torch 2. This process is described in detail in [Liu05].

### 2.4.2 Thermal mode complication

A problem arises in the slower thermal mode of the pulsed plasma torch. Because of the slow nature of the thermal mode, the transmission lines in figure 2.5 can no longer be regarded as transmission lines and act as normal wires. Therefore, in the thermal mode, all the connected torches are in parallel. If one of the torches has a lower impedance than the other torches, less current will flow in the other torches. The voltage-current characteristic of a thermal plasma is negative [Fau97][Cob58][Eng55], so a non-ideal current distribution will lead to a snowball-effect, in which one torch will become dominant. This can lead to an early extinguishment of the non-dominant torches [Hoy68]. A more thorough analysis is presented in appendix A.

To overcome this problem, series inductors are installed between the inductor L5 and the transmission lines. The goal is to achieve a homogenous energy distribution. Therefore, the series inductors should have equal values. Coupling these inductors could provide a better energy distribution over the multiple torches. This technique is however not tested, but will be recommended for future research.
Note that the inductor $L_5$ could be omitted in the case of the multiple thermal plasma torch in combination with the series inductors $L_{TL,x}$. This proves to be impractical, because the energy in the high voltage capacitor $C_{th}$ is transferred from the capacitor into the different inductors. Because of the parallel configuration, the inductance would be low, resulting in a high current in the thermal mode. The risk of the previously stated snowball-effect becomes higher. The inductors $L_{TL,x}$ should have a high inductance to overcome this problem.

Another solution is to install a common mode choke to prevent the current to flow from the inner conductor of one transmission line into the outer conductor of another transmission line. The series inductors $L_{TL1}$ until $L_{TL4}$ can be omitted in this case. Because of the long timescale of the current in the thermal mode, typically $500 \mu s$, magnetic material with a high magnetic permeability is needed. An iron core can provide this high magnetic permeability.

### 2.5 Pulsed thermal plasma model

The model for the pulsed thermal plasma will be divided into the transient model and the thermal model. The following pulsed thermal plasma model is proposed.

#### 2.5.1 Transient mode

![Transient mode model](image)

In case of transient plasma, the inductor consists of the inductance of the transmission line. The capacitor consists of the capacitance of the transmission line and, if present, the capacitor $C_{tr}$. Due to the low damping coefficient in the transient mode, the circuit is underdamped. The current in an underdamped circuit is

$$i(t) = \frac{V_0}{\omega d L} e^{-\alpha t} \sin(\omega d t)$$  

(2.1)

The derivation of equation 2.1 is included as appendix B.1. As stated before, the inductance $L$ and the capacitance $C$ are known. The value of the resistor $R$ is unknown. Appendix B.1.2 describes a technique to approximate this resistor by approximating the damping coefficient $\alpha$ with a measured current. The value of $\alpha$ is related to the resistance $R$ as shown in equation 2.2.

$$\alpha = \frac{R}{2L}$$  

(2.2)
2.5.2 Thermal mode

The model proposed for the thermal mode is shown in figure 2.8.

![Diagram of the thermal mode model]

In the thermal mode, the inductor consists of the coil $L_0$, the capacitor consists of the capacitor $C_{th}$. The circuit is the same with an exception to the diode $D$. Note that the high voltage capacitor $C_{tr}$ is omitted in the thermal mode model, since the current through the capacitor will be negligible compared to the current through the plasma. This assumption is described in appendix B.2.1.

A diode can be modeled by the Shockley ideal diode equation. It is impossible to solve this equation in this configuration, because the voltage over and the current through the diode are time-dependent and not known. An easier approach is modeling the diode with linear components. This is described in appendix B.2. The resulting equations are

\[
 i(t) = \frac{V_0}{\omega_d L} e^{-\alpha t} \sin(\omega_d t) \\
 i(t) = \frac{V_T + I_0 R + I_0 R_d}{R + R_d} e^{-\left(\frac{R + R_d}{L}\right)t} - \frac{V_T}{R + R_d}
\]

where the former equation is valid if diode $D$ is reversely biased. The latter equation holds if diode $D$ is forwardly biased. The constant $I_0$ is equal to the current which flows at the moment diode $D$ switches from reversely biased to forwardly biased. Therefore, the constant $I_0$ can be derived from equation 2.3. In equation 2.4, the constant $V_T$ and the constant $R_d$ stand for respectively the threshold voltage and the internal resistance of diode $D$. These constants are described in appendix B.2.2.
Chapter 3

Plasma torch

3.1 Plasma torch design

3.1.1 Construction

The measurements are performed on a custom made plasma torch. The plasma torch itself is a multiple wire-to-wire configuration spark gap. The spark gaps are placed in ceramic walls, so the torch can withstand high temperatures.

![Plasma torch construction](image)

Figure 3.1: Plasma torch construction

The air gap between two facing electrodes is about 8 millimeter.
3.1.2 Gas flow

The gas flow through the plasma torch is provided by a compressor. The advantage of using a compressor is the cold air that it produces, which is naturally dry. A dry air feed has the advantage of a more stable operation of the plasma torch.

To ensure the air flow inside the plasma torch is in the turbulent regime, the Reynolds number was calculated. The Reynolds number is defined as:

\[
Re = \frac{\rho v_s d}{\eta} = \frac{\rho V d}{\eta A}
\]

where \(d\) is the characteristic length of the cross-section and \(\eta\) is the dynamic viscosity of the medium. The characteristic length is equal to the diameter if the cross-section is circular.

Figure 3.2 shows the cross-section of the pulsed thermal plasma torch. The sizes in the figure are in millimeters. The diameter of the electrodes is 5 millimeter.

\[
\begin{array}{c|c|c}
\text{air flow [\ell s^{-1}]} & \text{Re [10^3]} \\
1.7 & 5 \\
2.75 & 8 \\
3.5 & 10 \\
4.4 & 13 \\
5.0 & 15 \\
\end{array}
\]

Table 3.1: Reynolds number for various flows

All these air flows are in the turbulent regime, since the critical Reynolds number is in the range 2000–2300 [Ols80].
3.1 Plasma torch design

3.1.3 Trigger pin

A triggering system was needed to provide a stable breakdown voltage, which leads to a more stable energy per pulse. To be able to trigger the plasma torch, a trigger pin was installed between the two electrodes of one of the plasma torches. The triggering circuit is analyzed in section 2.3.

![Trigger pin picture](image1)

![Trigger pin schematic view](image2)

Figure 3.3: Trigger pin

Figure 3.3 shows the trigger pin installed in the pulsed thermal plasma torch. The electrode is on the left, the trigger pin on the right. The air gap between the trigger pin and the nearby electrode is about 1 millimeter.
Chapter 3  Plasma torch

3.2 Design considerations

3.2.1 Triple points

The spark gap electrodes have no proper feedthroughs in the ceramic wall of the construction. This is visible in figure 3.4(a). Due to the small air gap between the ceramic wall and the electrode, a triple point exists, which causes field enhancement at the top and the bottom of the electrode [Wou02]. This field enhancement leads to a localized activity of the thermal plasma, which causes a poor distribution of electrode erosion.

![Triple points](image)

![Eroded electrode](image)

Figure 3.4: Electrode erosion

This is depicted in figure 3.4(b), the electrode erosion is visible mainly at the top right of the electrode. Note that the top of the electrode shown in the picture is facing the other electrode when it is correctly installed. The top left of the electrode also shows a higher erosion than the top of the electrode.

3.2.2 Electrode configuration

As previously noted, the configuration of the plasma torch is a wire-to-wire configuration. The wire electrodes are placed parallel to the gas flow. The bulk of the gas flow will not pass through the plasma zone, thus will remain untreated. A coaxial configuration of the plasma torch would overcome this problem.
Chapter 4

Measurement techniques

4.1 High voltage measurements

In order to attenuate the voltage signal, a high voltage probe is required. The one used in these measurements is the North Star Research Corporation PVM-1 high voltage probe. Figure 4.1 shows the equivalent circuit of the high voltage probe.

![Figure 4.1: Equivalent circuit of PVM-1 high voltage probe](image)

The known values are summed in table 4.1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R₁</td>
<td>400 MΩ</td>
</tr>
<tr>
<td>R₂</td>
<td>660 kΩ</td>
</tr>
<tr>
<td>C₁</td>
<td>6 pF</td>
</tr>
<tr>
<td>C₂</td>
<td>6 nF</td>
</tr>
</tbody>
</table>

The PVM-1 is an RC-divider which is balanced with the use of an 1 MΩ input impedance oscilloscope. The components R₃ and C₃ are used for calibration purposes. The high voltage probe attenuates the
Chapter 4 Measurement techniques

voltage by a factor 1000. The bandwidth of the high voltage probe is 80 MHz. Note that the coaxial cable is part of the high voltage probe; the capacitance of this cable is compensated when the probe was calibrated.

To prevent interference from electromagnetic compatibility, additional braids were tied around the coaxial cable and connected to the EMC-cabinet. A common mode choke was installed to minimize the influence of the high voltage probe.

4.2 Current measurements

The currents were measured using a Pearson 110 current monitor. The current monitor was connected to a 50 Ω impedance parallel to the oscilloscope. The sensitivity of the Pearson 110 current monitor is 0.05 Volt/Ampère in this configuration.

A Pearson 6600 current monitor was used in combination with the Pearson 110 current monitor in the case of the multiple pulsed thermal plasma torch. This current monitor was also connected to a 50 Ω impedance parallel to the oscilloscope.

Additional braids were tied around the coaxial cables and were connected to the EMC-cabinet to prevent electromagnetic compatibility interference.

4.3 Data recording

The TiePie HandyScope 3 was used to record the data. The oscilloscope provides a 12-bits vertical resolution with a sampling frequency of $50 \times 10^6$ samples per second. A 12-bits vertical resolution is necessary to record the transient mode and the thermal mode in one sample. In the case of the voltage, a breakdown voltage will be approximately 20 kV, while the amplitude of the thermal mode will be around 100 V. Suppose the vertical scale of an oscilloscope would be 40 V, then the voltage per bit of an 8-bit oscilloscope would be $\frac{40}{256} = 0.15625$ V/bit. Since the attenuation of the high voltage probe is 1000, this would correspond with 156.25 V/bit. As stated before, the voltage of the thermal mode will be around 100 V, this resolution would introduce a high level of quantization noise. In the case of a 12-bits oscilloscope, the voltage per bit would be $\frac{40}{4096} = 9.765625$ mV/bit. This would correspond with 9.765625 V/bit, because of the attenuation of the high voltage probe.

The TiePie HandyScope 3 was installed in a custom made EMC-cabinet to prevent electromagnetic compatibility interference. Common mode chokes were installed in the power cable and in the data cable.

A disadvantage of the TiePie HandyScope 3 is the lack of a hardware DC offset feature. This introduces a lower precision for signals of which the mean of the maximum peak and minimum peak is not close to 0 Volt. In the case of the pulsed plasma torch, the high voltage measurement signal fits this description. Therefore, a simple external DC offset device was installed. This device consists of a 9 Volt battery in parallel with some capacitors. This device was installed between the end of the cable of the high voltage probe and the input of the TiePie HandyScope. The capacitors provide a free path for the high frequency content in the signal, while the 9 Volt battery provides the DC offset. The equivalent circuit is included as figure 4.2.
4.4 Power and energy calculations

Since the voltages and the currents are measured, it is possible to calculate the power. To eliminate the noise of the voltage and the current disturbing the power calculation, data before the moment of trigger is set to zero.

\[ P(t) = \begin{cases} 0 & , \ t < 0 \\ v(t) \cdot i(t) & , \ t \geq 0 \end{cases} \]  
\[ P(t) \]

The integral of the power will result in the energy.

\[ E(t) = \int_0^t P(\tau) \cdot d\tau \]  
\[ E(t) \]

These formulas provide a way to calculate the energy per pulse.

4.4.1 Averaging

As stated before, the quantity of interest is the energy per pulse. Because of fluctuation of the energy per pulse, averaging is required. Earlier work on the pulsed thermal plasma torch describes an averaging measurement on the separate signals, the voltage and the current [Waa04]. This technique is not valid since:

\[ \int_0^t \overline{v(\tau)} \cdot \overline{i(\tau)} d\tau \neq \int_0^t \overline{v(\tau)} \cdot \overline{i(\tau)} d\tau = \overline{E} \]

If the voltage and the current are stable from shot to shot, then \( \overline{v(t)} \cdot \overline{i(t)} \approx \overline{v(t) \cdot i(t)} \). Thus averaging the separate signals can provide accurate results if this condition is met. Nevertheless, in this research the individual energies per pulse were calculated and averaged afterwards to eliminate this room for error.
4.4.2 Transient and thermal mode

To divide the energy dissipated in the transient and in the thermal mode of the pulsed plasma torch, the energy at the end of the oscillatory period is taken from the energy signal. The end of the oscillatory period is typically 0.5 \( \mu \text{s} \). The end of the transient mode was detected by the zero-crossings of the current.

4.5 Temperature measurement

The inlet and outlet temperature are measured with a K-type thermocouple. The thermometer used in this research is the HH-25KC of the Omega Engineering company\(^1\). The resolution of this thermometer is 0.1 °C in the range of -40 °C to 199.99 °C. The thermometer was placed in a custom made EMC-cabinet to reduce the electromagnetic compatibility interference. Additional braids were tied around the cables of the probe and connected to the custom made EMC-cabinet. The thermocouple error has been analyzed by measuring the temperature of boiling water at different surrounding temperatures. The measured temperature was at all times in the range 103 °C–104 °C. The difference between the two different probes used in this research turned out to be negligible. A thermocouple does not provide a high time resolution since the probes need to heat before an accurate measurement can be made. Detecting distinct differences between the transient mode and the thermal mode of the pulsed thermal plasma torch in a single pulse is therefore impossible.

4.6 Plasma diagnostics

4.6.1 Heat production

The heat production of the plasma is analyzed by measuring the inlet and outlet temperature. The temperature difference is used to calculate the heat flow caused by the plasma.

\[
\dot{Q} = c_p \dot{m} \Delta T \quad (4.6)
\]

The mass flow of atmospheric air is derived using the volume flow;

\[
m = \rho V \quad (4.7)
\]

\[
\dot{m} = \frac{d(\rho V)}{dt} = \rho \frac{dV}{dt} + V \frac{d\rho}{dt} \quad (4.8)
\]

\[
= \rho \frac{dV}{dt} + V \frac{d\rho}{dt} \frac{dT}{dt}
\]

Assuming the mass density does not depend on time (thus not on temperature), the equation above will result in:

\[
\dot{m} = \rho \dot{V} \quad (4.9)
\]

\(^1\)http://www.omega.com
The above assumption can be made because of the relatively low temperature rise and the low temperature dependance of the mass density of air in this temperature range.

\[ \dot{Q} = c_p \rho \dot{V} \Delta T \] (4.10)
Chapter 5

Measurement results

5.1 Typical waveforms

A typical voltage measurement is shown in figure 5.1(a), a typical current measurement is shown in figure 5.1(b). More details can be seen in figure 5.2.

(a) Typical voltage waveform  
(b) Typical current waveform

Figure 5.1: Typical waveforms
The transient mode and the thermal mode are visible in figure 5.2.

(a) Transient mode voltage  
(b) Thermal mode voltage  
(c) Transient mode current  
(d) Thermal mode current

Figure 5.2: Transient and thermal mode

The transient mode shows the oscillatory period, this is clearly visible in figure 5.2(c). The current in the thermal mode slowly decays, while the voltage is more or less stable.

As stated in section 4.4, the energy can be calculated using the voltage and current. Figure 5.3 shows the outcome of this calculation for this signal.

The short transient mode is clearly visible, as the energy in the transient mode is dissipated faster than the energy in the thermal mode.
5.2 Stability

The effect of triggering the pulsed plasma torch is shown in figure 5.4. The measurement consists of 1000 samples taken from a torch without triggering and a torch with triggering. The effect is visible in the energy per pulse histograms. Furthermore, the histograms resemble gaussian probability distributions.

It is evident that triggering the pulsed thermal plasma torch has a positive effect on the energy per pulse stability and therefore also on the stability of the electric power input of the pulsed thermal plasma torch.

Assuming a gaussian distribution of the energy per pulse, the standard deviation can be calculated using the following formula.

\[
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \overline{x})^2}
\]  

(5.1)
Chapter 5  Measurement results

\[
\begin{align*}
\sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i^2) - \frac{2}{N} \sum_{i=1}^{N} (x_i \bar{x}) + \frac{1}{N} \sum_{i=1}^{N} (\bar{x}^2)} \\
\sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i^2) - \frac{2}{N} \sum_{i=1}^{N} (x_i) + \bar{x}^2} \\
\sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i^2)}
\end{align*}
\] (5.2)

Formula 5.1 is used in Matlab, formula 5.2 is used in the C++ routine included as appendix C.4. The latter formula is easier to implement in the C++ programming language.

Performing a running averaging measurement, the minimum number of samples can be determined. The standard deviation versus the number of samples is shown in figure 5.5. Note that the standard deviation \( \sigma \) is divided by the arithmetic mean \( \mu \) of the energy per pulse. The standard deviation is therefore in this case dimensionless.

It is obvious that the higher the number of samples, the more accurate an averaging measurement will represent the ensemble. Nevertheless, figure 5.5 shows that after a limited amount of samples, the standard deviation converges to a stable value. In this case, the 1000 samples do not provide a significant better representation of the ensemble than the first 100 samples.

To create the possibility of postprocessing of the data, all the measured data is saved before averaging. Because of memory constraints, a limited number of samples can be taken. The number of samples taken in this research is 64.

5.3  Model validation

The model proposed in section 2.5 was validated by measurements. The model is analyzed using the configuration given in table 5.1.

To compare the model to the measurements, a routine was developed in MATLAB. This routine is included as appendix C.6.
5.3 Model validation

<table>
<thead>
<tr>
<th>( C_L ) [F]</th>
<th>( C_{th} ) [F]</th>
<th>( L_5 ) [H]</th>
<th>( C_{tr} ) [F]</th>
<th>( L_{tr} ) [H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 ( \mu )</td>
<td>11.8n</td>
<td>3.4m</td>
<td>--</td>
<td>975n</td>
</tr>
</tbody>
</table>

Table 5.1: Configuration used in model validation

5.3.1 Transient mode

The result of the modeled current in the transient mode is shown in figure 5.6(a). Since it is known that \( v(t) = R \cdot i(t) \), the modeled current can be transformed to a modeled voltage. Figure 5.6(b) shows the comparison of the modeled voltage and the measured voltage in the transient mode.

![Measured and modeled current](image1)

(a) Measured and modeled current

![Measured and modeled voltage](image2)

(b) Measured and modeled voltage

Figure 5.6: Transient model comparison

The modeled current coincides with the measured current. However, the modeled voltage and the measured voltage are different. The simplicity of the transient model affects the model validity. The transmission line is modeled as an LC combination, which is not entirely valid. Furthermore, the plasma itself does not behave as a linear element.

The resistance found by the iterative resistance routine included as appendix B.1.2 was found in the range 1–5 \( \Omega \).

5.3.2 Thermal mode

The thermal mode model result is shown in figure 5.7.

Again the modeled current coincides with the measured current. It can be concluded that from the current’s point of view, the pulsed thermal plasma torch can be modeled as a resistance. The difficulty remains the value of this resistance. Appendix B.1.2 describes a technique to retrieve the damping coefficient of the transient mode, which leads to the resistance. This resistance holds for the current in the transient mode as well as for the thermal mode. The typical resistance was found to be in the range 1–5 \( \Omega \).

The modeled voltage is discrepant to the measured voltage. The simplicity of the thermal mode model plays an important role here. If the transient capacitor \( C_{tr} \) would be included, the result could be better. Furthermore, it is known that the voltage-current characteristic of a thermal plasma is negative [Fau97].
Chapter 5  Measurement results

(a) Measured and modeled current  
(b) Measured and modeled voltage

Figure 5.7: Transient model comparison

Conclusion

The pulsed thermal plasma model is validated for the current. The modeled voltage and the measured voltage are discrepant, mainly due to the simplicity of the model and the non-linearity of a thermal plasma. The pulsed thermal plasma model can be used to estimate the pulse shape parameters. The role of the components that control the pulse shape can be retrieved from the pulsed thermal plasma model.

The pulsed thermal plasma model would not be suited for simulations yet. Because of the discrepancy between the modeled voltage and the measured voltage, a modeled energy would not be valid. The impedance of the thermal plasma cannot be modeled by a fixed resistor for these applications. A more sophisticated thermal plasma model that would take the negative voltage-current characteristic of a thermal plasma into account could make simulations possible.

5.4 Configurations

As stated in section 2.2 and in section 2.5, characteristics of the transient mode and the thermal mode can be adjusted by altering the values of the components. Three different configurations were investigated, the values are are shown in table 5.2.

<table>
<thead>
<tr>
<th>#</th>
<th>CL [F]</th>
<th>Cth [F]</th>
<th>L5 [H]</th>
<th>Ct [F]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.2μ</td>
<td>3.3n</td>
<td>1.5m</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>2.2μ</td>
<td>2n</td>
<td>1.5m</td>
<td>1.3n</td>
</tr>
<tr>
<td>3</td>
<td>2.2μ</td>
<td>2n</td>
<td>4.5m</td>
<td>1.3n</td>
</tr>
</tbody>
</table>

Table 5.2: Configurations

5.4.1 Plasma diagnostics

For each of the three circuit configurations, the heat produced by the plasma was measured at various flows. The differences between the different configurations are negligible. Therefore, only configura-
tion 1 is shown in figure 5.8. A compressor was used to provide the necessary pressure. The advantage of using a compressor is the dry air it provides, since the outlet temperature of the compressor is 4 °C. The measurement data is included in appendix D.

For every single gas flow, the inlet temperature, the outlet temperature and the energy per pulse was measured at different repetition rates of the pulse source. The temperature difference is linear with the pulse repetition rate, as can be seen in figure 5.8(a). The repetition rate seems to have a low effect on the energy per pulse in this configuration, which results in a linear electrical power input into the pulsed thermal plasma torch as can be seen in figure 5.8(b).

The heat flow also shows a linear pattern with respect to the repetition rate. This is in correspondence with the expectation, since the temperature difference was linear with respect to the repetition rate. More importantly, the heat flow seems to be indifferent to the gas flow, as figure 5.8(c) shows. Therefore, the heat flow appears to be linear with respect to the electrical input power.

**Conclusion**

The efficiency of heating the air is depicted in figure 5.8(d), the efficiency of the pulsed thermal plasma torch is in the range of 60%-70%. This is consistent with earlier work on the pulsed thermal plasma
Chapter 5 Measurement results

torch [Bar03].

5.4.2 Energy per pulse

With these different configurations shown in table 5.2, the energy balance was measured to investigate the difference of the thermal characteristics of the pulsed thermal plasma torch. Figure 5.9 shows the mean energy per pulse in the three different configurations. The two bars for each configuration stand for different points in time. The differences between the two bars are marginal, which means the measurements are successfully reproduced. The energies per pulse are measured at various flows and at different repetition rates, but since the energies per pulse are not or only little dependent on the gas flow and the repetition rate, these values are averaged. Every bar consists of an average of 320 measurements, 64 measurements per setting for 10 different repetition rates and for 5 different gas flows. Both the transient mode and the thermal mode energy are visible in figure 5.9.

![Figure 5.9: Energy Per Pulse comparison](image)

The differences between configuration 2 and configuration 3 are negligible. However, the difference between configuration 1 and configuration 2 is substantial. This is in correspondence with the expectation, since configuration 2 and configuration 3 have a higher value for the transient capacitance. The thermal mode energy in configuration 1 is higher, because of the higher value of the thermal mode capacitor, $C_{th}$. The differences between configuration 2 and configuration 3 are visible in the pulse length.
5.4 Configurations

5.4.3 Stability

The stability is analyzed by comparing the standard deviation of the energy per pulse. The standard deviation is divided by the arithmetic mean of the energy per pulse, which results in a dimensionless standard deviation.

![Figure 5.10: Standard deviation Energy Per Pulse comparison](image)

The comparison with respect to the standard deviation of the energy per pulse between the different configurations show that configuration 3 has a significant lower standard deviation than the other two configurations. The stability of the pulsed thermal plasma torch is drastically improved by a higher inductance, which can be controlled by inductor L5.

5.4.4 Pulse length

The pulse length can be varied by adjusting the inductor L5, according to the pulsed thermal plasma model. Figure 5.11 shows that this expectation is valid for the pulsed thermal plasma torch.

![Figure 5.11: Pulse length comparison](image)

The major difference in the transient mode is between configuration 1 and the other two configurations. This is similar to the energy in the transient mode as seen in section 5.4.2. Furthermore, this
Chapter 5 Measurement results

is in accordance with the pulsed thermal plasma model, since the resonant frequency of the thermal mode changes when the capacitance of the transient mode changes. The significant difference in the thermal mode is between configuration 3 and the other two configurations. The inductance of the thermal mode is higher in configuration 3, leading to a lower damping coefficient. The current decay is therefore smaller, which results in a longer pulse length.

5.4.5 Current thermal mode

The current in the thermal mode is the important parameter for the thermal mode. The mean current and the maximum current in the thermal mode are compared against the three configurations in figure 5.12.

![Figure 5.12: Thermal mode current](image)

According to the model, the highest current would be configuration 2, since the inductance and the capacitance are the lowest in this setting. This results in a higher frequency and a higher amplitude of the oscillation period in the thermal mode, as can be seen in equation 2.3. Figure 5.12 corresponds with this expectation.

The maximum current in the thermal mode of configuration 1 is lower because of the higher thermal mode capacitance. The maximum current in configuration 3 is lower compared to configuration 2 because the inductance of the thermal mode is higher.

The mean current in the thermal mode is dependant on the maximum current in the thermal mode, the thermal mode duration and the energy of the thermal mode. Considering the figures 5.9, 5.11(b) and 5.12, the highest mean current is expected for configuration 1, because of the higher energy in the thermal mode. The shorter pulse length results in a higher mean thermal mode current in configuration 2 than configuration 3.

5.5 Multiple torches

To provide a higher plasma volume, multiple torches are necessary. The two configurations that were investigated are reported in section 2.4, where the reason for extra precautions in the multiple torches configuration is explained. The reason for a non-homogenous energy distribution can be seen in figure 5.13.

The dominance of torch 2 is clearly visible in figure 5.13(b). The current through torch 1 in the transient mode coincides with the current through torch 2 as can be seen in figure 5.13(a), but the
thermal mode is clearly different. Torch 1 does not reach the same peak current in the thermal mode as torch 2, which results in a fast decay and an early extinguishment for torch 1.

Note that figure 5.13 does not represent a worst-case situation. If no precautions are taken, a 100% unbalance can occur, where the thermal mode energy of the pulsed thermal plasma torch is dissipated in a single torch.

5.5.1 Series inductors

The values of the components used in the multiple thermal plasma torch measurements are given in table 5.3. Note that the LTL inductors have similar values for all transmission lines.

<table>
<thead>
<tr>
<th>LTLx [H]</th>
<th>Cth [F]</th>
<th>Lx [H]</th>
<th>Cx [F]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4m</td>
<td>2n</td>
<td>3.6m</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 5.3: Multiple torches configuration

Two torches

At first, only two torches are connected. The pulsed thermal plasma is independent of the air flow as seen in section 5.4.1. Therefore, only one air flow was investigated at this point. The air flow used in this research from this point onwards is 3.5 ℓ s⁻¹.

The quantity of interest is the energy per pulse per torch. A homogenous energy distribution among the torches is required to make the multiple torches configuration viable.

The energy distribution among the two torches connected is shown in figure 5.14.

It can be seen that the distribution is not ideal, torch 1 dissipates about 40% of the energy. The values of the inductors LTLx are in this case not exactly identical. In practice it proved to be difficult to get an even energy distribution among the torches. The energy distribution depends on both the transient mode and the thermal mode, which makes a homogenous energy distribution complicated to realize.
Chapter 5 Measurement results

Four torches

Four torches were connected using the same components as in the two torches configuration. The energy distribution among the four torches can be seen in figure 5.15.

The energy distribution gets more uneven, the difference between torch 1 and torch 4 is large. Torch 2 dissipates about 50% of torch 4. This could be an undesired result for future applications. To even out the energy distribution among the torches, the inductors $L_{TL,x}$ could be magnetically coupled. This is recommended for future research.

5.5.2 Choking coil

A different approach to prevent a non-homogenous energy distribution is to implement a choking coil in the transmission lines. The choking coil will reduce the common mode current through the transmission lines, which could result in a better energy distribution among the several torches. The configuration is the same as in table 5.3, without the series inductors $L_{TL,x}$. The choking coil implemented consists of an iron core and eight windings from each of the transmission lines. Because of practical reasons, the choking coil was only investigated for two pulsed thermal plasma torches.
5.5 Multiple torches

Figure 5.16: Energy distribution among two torches

5.5.3 Conclusion

The energy distribution among the torches seems better in the case of the choking coil. Note the difference between the energy dissipation in the transient mode. While the choking coil seems to work for the thermal mode, the transient mode energy distribution is not optimal. This is due to the differences in the voltage in the transient mode. This is visible in figure 5.17.

Figure 5.17: Unbalanced multiple pulsed plasma torch voltage

The voltage in the thermal mode over torch 1 coincides with the voltage over torch 2. The thermal mode energy distribution is therefore dependant on the current distribution. However, the voltage over torch 1 in the transient mode does not coincide with the voltage over torch 2. Therefore, the energy distribution in the transient mode is dependant on the voltage distribution among the several torches. The two techniques that are investigated are designed to provide a better current distribution. The voltage distribution is not controlled, it is shown that this is necessary to provide an even energy distribution among the several torches.

The current distribution is more homogeneous in the case of the choking coil. Therefore, the choking coil would be a better option. Nevertheless, a choking coil must consist of all the transmission lines and preferably an iron core. This could make this option expensive.

Magnetically coupling of the series inductors could prove to be difficult, since the series inductors
should be magnetically coupled in pairs. This could lead to a complex structure in the case of multiple pulsed thermal plasma torches.
Chapter 6

Conclusions and recommendations

6.1 Conclusions

- The thermal balance of the pulsed thermal plasma torch is independent from the gas flow. About 60%-70% of the electrical energy dissipated in the thermal plasma is converted to heat absorbed by the surrounding air.

- Pulse shapes do not seem to play an important role in the energy balance of the pulsed thermal plasma torch. Different pulse shapes that were investigated convert about 60%-70% of electrical energy into heat.

- The pulsed thermal plasma model is valid for the current. The model is not valid for the voltage, due to the non-linear behavior of an arc. Therefore, the pulsed thermal plasma model is not suited for voltage simulations. By using the pulsed thermal plasma model, one gains an insight in the functioning of the circuit. Furthermore, different parameters can be estimated from this model, such as pulse length and current amplitude.

- A single pulse source can drive several pulsed thermal plasma torches. Synchronization of the plasma torches is possible. To ensure a homogenous energy distribution among the several torches, adjustments to the single pulsed thermal plasma torch circuit are necessary.

6.2 Recommendations

- The custom made pulsed plasma torch reactor is suitable for the energy balance of the pulsed plasma. Applications such as plasma spraying, plasma chemistry and others are not suitable for this plasma torch reactor. For these applications, a coaxial electrode configuration is preferable.

- To ensure a homogenous energy distribution of the multiple pulsed thermal plasma torch, the series inductors could be magnetically coupled. This would provide a homogenous current through the multiple torches, and therefore, a homogenous energy distribution. This can also be achieved by a choking coil, consisting of the transmission line and preferably an iron core.

- The energy in the high voltage part of the circuit is not fully discharged into the plasma. Mainly the thermal mode inductor L₅ seems to be an obstruction for the energy flow. Since
Chapter 6  Conclusions and recommendations

the impedance of thermal plasma is low, the DC resistance of the inductor \( L_5 \) cannot be neglected.

- To analyze the difference between the transient mode and the thermal mode of the pulsed thermal plasma torch, more advanced plasma diagnostics techniques are required. Quantities of interest would be light emission, chemical activity, radical species production and temperature.

- Expand the number of configurations and analyze the physical plasma differences between the several pulse shapes driving the plasma torch.

- Extend the pulsed thermal plasma torch model with an impedance for the plasma to obtain the pulse shape parameters. This would provide a way to estimate the energy per pulse.
Bibliography


List of Figures

2.1 Pulsed plasma torch circuit .................................................. 5
2.2 High voltage part ................................................................. 6
2.3 Schematic waveforms ............................................................. 6
2.4 Trigger circuit ................................................................. 7
2.5 Multiple torches circuit ......................................................... 8
2.6 Equivalent circuit for a two torch configuration ....................... 8
2.7 Transient mode model .......................................................... 9
2.8 Thermal mode model .......................................................... 10
3.1 Plasma torch construction ...................................................... 11
3.2 ................................................................. 12
3.3 Trigger pin ................................................................. 13
3.4 Electrode erosion ............................................................... 14
4.1 Equivalent circuit of PVM-1 high voltage probe ...................... 15
4.2 Offset circuit ................................................................. 17
5.1 Typical waveforms ............................................................. 21
5.2 Transient and thermal mode .................................................. 22
5.3 Energy transient ............................................................... 23
5.4 Energy Per Pulse Histogram .................................................. 23
5.5 Standard deviation convergence .............................................. 24
5.6 Transient model comparison .................................................. 25
5.7 Transient model comparison .................................................. 26
5.8 Heat measurement figures ..................................................... 27
5.9 Energy Per Pulse comparison .................................................. 28
5.10 Standard deviation Energy Per Pulse comparison ..................... 29
5.11 Pulse length comparison ....................................................... 29
5.12 Thermal mode current ......................................................... 30
5.13 Unbalanced multiple pulsed plasma torch current .................... 31
5.14 Energy distribution among two torches ................................... 31
5.15 Energy distribution among four torches .................................. 32
5.16 Energy distribution among two torches .................................. 33
5.17 Unbalanced multiple pulsed plasma torch voltage ..................... 33
A.1 Unstable configuration ......................................................... 45
A.2 Stable configuration .......................................................... 46
LIST OF FIGURES

A.3 Stable configuration ............................................. 46
A.4 Unstable multiple torch configuration ......................... 47
B.1 Thermal mode model equivalent circuit ....................... 53
List of Symbols

\( C \) capacitance
\( C_m \) capacitance of transmission line per meter
\( E \) energy
\( L \) inductance
\( L_m \) inductance of transmission line per meter
\( P \) power
\( \dot{Q} \) heat flow
\( T \) temperature
\( V \) volume
\( \dot{V} \) volume flow
\( V_0 \) initial voltage
\( Z_0 \) characteristic impedance
\( c_p \) specific heat density
\( d \) characteristic length
\( i \) current
\( m \) mass
\( \dot{m} \) mass flow
\( t \) time
\( v \) voltage
\( v_s \) velocity
\( \bar{x} \) arithmetic mean of x, \( \frac{1}{N} \sum_{i=1}^{N} x_i \)
\( \alpha \) damping coefficient
LIST OF SYMBOLS

\( \eta \)  dynamic viscosity
\( \mu \)  arithmetic mean
\( \omega_0 \)  resonant frequency
\( \omega_d \)  damped frequency
\( \rho \)  mass density
\( \sigma \)  standard deviation
Acknowledgements

At this point I would like to thank everyone who helped me during my project. Firstly, I would like to thank dr. Guus Pemen and prof. Jan Blom for creating the possibility to graduate at the Pulsed Power group. The research project proved to be difficult from time to time, which led to a challenging project where different engineering skills were required. The project included a wide range of aspects, this proved to be very instructive.

I owe much gratitude to the staff of the Pulsed Power group; dr. Guus Pemen, dr. Bert van Heesch, dr. Keping Yan, ir. Hans Winands and Zhen Liu M.Sc. for their useful advice and for sharing their expertise with me. Furthermore, they provided a pleasant work atmosphere, which drove me to perform better.

Last but not least I would like to thank the students who worked on their projects in the same sub-department as I did. Their willingness to help me and their useful tips encouraged and helped me to realize this project.
Appendix A

Multiple torch complication

As stated in section 2.4, the multiple torch configuration needs prerequisites to guarantee a homogeneous energy distribution. The derivative of the voltage over a thermal plasma with respect to the current is negative,

$$\frac{dv_p}{di_p} < 0$$

where $v_p$ is the voltage drop over the thermal plasma and $i_p$ the current through the thermal plasma.

A.1 Unstable operation

Consider the circuit in figure A.1(a). The plasma torch is connected to an ideal voltage source.

![Unstable circuit and V-I characteristic](image)

Figure A.1: Unstable configuration

Suppose the equilibrium situation exists depicted in figure A.1(b). Note that an infinitesimal increase in current results in a voltage decrease over the thermal plasma. The voltage source will have an excess voltage and tends to push more current through the thermal plasma, enhancing the unbalance.

A.2 Stable operation

Now consider the circuit in figure A.2(a).
The resistor in the circuit prevents the unbalance this configuration. The overall voltage-current characteristic of the load is rising from a certain point onwards. An equilibrium situation exists where the voltage source voltage-current characteristic intersects the voltage-current characteristic of the total load. Suppose an infinitesimal increase in the thermal plasma current occurs. The voltage over the total load will increase. The voltage source will suppress this excess voltage of the load by reducing the current. Note that a infinitesimal decrease in current results in a sign reversal. Therefore, this circuit will be stable. The voltage-current characteristic of the voltage source in combination with the resistor is depicted in figure A.3(b).

In the case of an infinitesimal increase of the current, the voltage drop over the resistor will increase, which results in a decrease of the voltage at the terminal of the resistor. According to the voltage-current characteristic of the thermal plasma, the voltage drop over the plasma will also decrease. Nevertheless, this voltage drop decrease will be smaller than the voltage drop decrease over the resistor. In the case of the plasma, the increase in current and slight decrease of voltage results in a demand for extra electrical power. However, the voltage source in combination with the resistor cannot provide this extra electrical power, because of the decrease of the voltage. Therefore, the current will decrease to the equilibrium position. Because of this, the thermal plasma is not voltage-controlled, but power-controlled.
Note that the voltage source in combination with the resistor can represent more complex circuits according to Thévenin's theorem.

### A.3 Multiple torch operation

Consider the multiple torch configuration in figure A.4(a).

![Multiple torch circuit](image)

(a) Multiple torch circuit

![V-I characteristic](image)

(b) V-I characteristic

Figure A.4: Unstable multiple torch configuration

The two thermal plasma torches are connected in parallel to the voltage source with series resistor. The voltage-current characteristic of this configuration is depicted in figure A.4(b). Note the differences between the voltage-current characteristics of torch 1 and torch 2. This difference is caused by a slight difference in electrode distance. A common equilibrium position does not exist because of this difference. Consider a similar situation as in section A.2, torch 1 is in its equilibrium position. In the case of an infinitesimal increase of the current, the voltage source in combination with the resistor cannot provide the extra power. Nevertheless, the extra power can be provided by diminishing the power consumption of torch 2. As stated in section A.2, thermal plasmas are not voltage-controlled, but power-controlled. The component that can control the power consumption is the resistor. However, this single resistor can never control the power consumption of two parallel thermal plasma torches.

### A.4 Solutions

Different approaches exist to overcome the problem of the multiple torch configuration. The two techniques in this research use the following approaches.

- Provide power control to every single thermal plasma torch
- Disturb the parallel configuration of the thermal plasma torches

The former option is realized by adding series inductors for every single plasma torch and is described in section 2.4.2. The common mode choke in section 2.4.2 is based on the latter option.
Appendix B

RLC circuit analysis

B.1 RLC circuit

The current in a RLC circuit with a capacitor that will discharge is derived as follows [Smi02]:

\[
\begin{align*}
    i(t) &= i_C(t) = i_L(t) = i_R(t) \\
    0 &= v_C(t) + v_L(t) + v_R(t) \\
    0 &= \frac{1}{C} \int_0^t i(\tau)d\tau + v_C(0) + L\frac{di(t)}{dt} + i(t)R \\
    0 &= L\frac{d^2i(t)}{dt^2} + R\frac{di(t)}{dt} + \frac{1}{C}i(t)
\end{align*}
\]

A solution of the linear second-order homogenous differential equation is attempted

\[
i(t) = e^{mt}
\]

Substitution leads to

\[
\begin{align*}
    0 &= Lm^2e^{mt} + Rme^{mt} + \frac{1}{C}e^{mt} \\
    0 &= Lm^2 + Rm + \frac{1}{C} \\
    m_{1,2} &= \frac{-R \pm \sqrt{R^2 - \frac{4L}{C}}}{2L} \\
    m_{1,2} &= -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \\
    m_{1,2} &= -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}
\end{align*}
\]
Appendix B  RLC circuit analysis

B.1.1 Underdamping

The case of underdamping is examined further

\[ \alpha^2 < \omega_0^2 \]

which leads to

\[ m_{1,2} = -\alpha \pm j\omega_d \]
\[ \omega_d^2 = \omega_0^2 - \alpha^2 \]

Substitution:

\[ i(t) = A_1 e^{m_1 t} + A_2 e^{m_2 t} \]

Before the switch is closed, the current is 0, therefore

\[ i(t = 0^-) = 0 \]
\[ A_1 + A_2 = 0 \]
\[ A_1 = -A_2 \]

Right after the switch is closed, the inductor will have a high impedance, therefore the voltage over the inductor will approximately be \( V_0 \).

\[ t = 0^+ \Rightarrow V_0 = L \frac{di(t)}{dt} \]
\[ \left( \frac{di(t)}{dt} \right)_{t=0^+} = \frac{V_0}{L} \]
\[ \left( \frac{di(t)}{dt} \right)_{t=0^+} = A_1 m_1 + A_2 m_2 \]
\[ A_1 (-\alpha + j\omega_d) + A_2 (-\alpha - j\omega_d) = \frac{V_0}{L} \]
\[ A_1 (-\alpha + j\omega_d) - A_1 (-\alpha - j\omega_d) = \frac{V_0}{L} \]
\[ 2jA_1\omega_d = \frac{V_0}{L} \]
\[ A_1 = \frac{V_0}{2j\omega_d L} \]

Substituting \( A_1 \) leads to

\[ i(t) = \frac{V_0}{2j\omega_d L} \left( e^{(-\alpha+j\omega)d} - e^{(-\alpha-j\omega)d} \right) \]
\[ i(t) = \frac{V_0}{2j\omega_d L} e^{-\alpha t} \left( e^{j\omega t} - e^{-j\omega t} \right) \]
\[ i(t) = \frac{V_0}{\omega_d L} e^{-\alpha t} \sin(\omega_d t) \]

which leads to the current in a RLC circuit.
B.1.2 Damping coefficient

Suppose the current is known, but the resistive element \( R \) is unknown. The damping constant \( \alpha \) can be found according to the following equations.

\[
\frac{i^2(t)}{L} = \left( \frac{V_0}{\omega_d L} \right)^2 e^{-2\alpha t} \sin^2(\omega_d t)
\]

\[
i^2(t) = \left( \frac{V_0}{\omega_d L} \right)^2 e^{-2\alpha t} \left( -\frac{1}{2} \cos(2\omega_d t) + \frac{1}{2} \right)
\]

\[
i^2(t) = -\frac{1}{2} \left( \frac{V_0}{\omega_d L} \right)^2 e^{-2\alpha t} \cos(2\omega_d t) + \frac{1}{2} \left( \frac{V_0}{\omega_d L} \right)^2 e^{-2\alpha t}
\]

Filtering out the high frequency term results in \( \overline{i^2(t)} \)

\[
\overline{i^2(t)} = \frac{1}{2} \left( \frac{V_0}{\omega_d L} \right)^2 e^{-2\alpha t}
\]

\[
e^{-2\alpha t} = 2 \left( \frac{\omega_d L}{V_0} \right)^2 \cdot \overline{i^2(t)}
\]

\[
-2\alpha = \ln \left[ 2 \left( \frac{\omega_d L}{V_0} \right)^2 \cdot \overline{i^2(t)} \right]
\]

\[
-2\alpha = \ln[2] + \ln \left[ \left( \frac{\omega_d L}{V_0} \right)^2 \right] + \ln \left[ \overline{i^2(t)} \right]
\]

\[
-2\alpha = \ln[2] + 2 \ln \left[ \frac{\omega_d L}{V_0} \right] + \ln \left[ \overline{i^2(t)} \right]
\]

\[
\alpha t = -\frac{1}{2} \ln[2] - \ln \left[ \frac{\omega_d L}{V_0} \right] - \frac{1}{2} \ln \left[ \overline{i^2(t)} \right]
\]

\[
\alpha t = -\ln[\sqrt{2}] + \ln \left[ \frac{V_0}{\omega_d L} \right] - \ln \left[ \sqrt{\overline{i^2(t)}} \right]
\]

\[
\alpha t = \ln \left[ \frac{V_0}{L \sqrt{2\overline{i^2(t)}}} \right] - \ln[\omega_d]
\]

\[
\alpha t = \ln \left[ \frac{V_0}{L \sqrt{2\overline{i^2(t)}}} \right] - \ln[\omega_0 - \alpha]
\]

where the second part of the latter equation depends on the damping coefficient \( \alpha \). By introducing an initial value variable \( \alpha' \), the damping coefficient \( \alpha \) can be found iteratively.

\[
\alpha t = \ln \left[ \frac{V_0}{L \sqrt{2\overline{i^2(t)}}} \right] - \ln[\omega_0 - \alpha']
\]

Initial value analysis

\[
\omega_d^2 = \omega_0^2 - \alpha^2
\]
Appendix B  RLC circuit analysis

\[ \omega_d^2 = \frac{1}{LC} - \left( \frac{R}{2L} \right)^2 \]

Introducing the inductance per meter \( L_m \) and the capacitance per meter \( C_m \) and the length \( l \) of the transmission line.

\[
\begin{align*}
\omega_d &= \frac{1}{l\sqrt{L_mC_m}} - \frac{R}{2lL_m} \\
\omega_d &= \frac{1}{l} \left( \frac{1}{\sqrt{L_mC_m}} - \frac{R}{2L_m} \right)
\end{align*}
\]

Since the type of the transmission line is known (RG217), the capacitance and the inductance can be retrieved from the specifications.

| \( Z_0 \) | 50 \( \Omega \) |
| \( C_m \) | 100 pF m\(^{-1}\) |

\[ Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{L_m}{C_m}} \]

\[ L_m = Z_0^2 C_m \]

\[ L_m = 50^2 \cdot 100 \cdot 10^{-12} \]

\[ L_m = 250 \cdot 10^{-9} \text{ H m}^{-1} \]

leads to

\[
\begin{align*}
\omega_d &= \frac{1}{l} \left( \frac{1}{\sqrt{L_mC_m}} - \frac{R}{2L_m} \right) \\
\omega_d &= \frac{1}{l} \left( 2 \cdot 10^8 - 2 \cdot 10^6 R \right) \\
\omega_d &= \frac{2 \cdot 10^6}{l} \left( 100 - R \right)
\end{align*}
\]

where can be seen that if the resistive element \( R \) is small (\( R \ll 100 \\Omega \)), the damped frequency will be almost equal to the resonant frequency. In the case of the pulsed thermal plasma torch, the resistance is assumed to be much smaller than 100 \( \Omega \). Therefore, a good initial value for the damping coefficient \( \alpha \) would be zero, i.e. \( \alpha' = 0 \).

B.2  RLC circuit with diode

The diode is modeled by a voltage source \( V_T \) and a resistor \( R_d \) if the voltage over the diode is higher than the threshold voltage. If the voltage is lower than the threshold voltage, the diode is modeled as an open circuit.

\[
\begin{align*}
i_d(t) &= 0, \quad v_d(t) - V_T < 0 \\
i_d(t) &= \frac{v_d(t) - V_T}{R_d}, \quad v_d(t) - V_T > 0
\end{align*}
\]

where \( v_d(t) \) is the voltage over the diode.
B.2 RLC circuit with diode

Figure B.1: Thermal mode model equivalent circuit

B.2.1 Reversely biased diode

In the case of a reversely biased diode, the circuit is equivalent to the RLC circuit in the transient mode model, therefore

\[ i(t) = \frac{V_0}{\omega_d L} e^{-\alpha t} \sin(\omega_d t) \]

The capacitor \( C_{tr} \) in figure 2.2 is omitted in the thermal mode model. The influence of capacitor \( C_{tr} \) is negligible if

\[ \frac{1}{\omega_d C_{tr}} \gg R \]

\[ \omega_d \ll \frac{1}{RC_{tr}} \]

This condition must be met to validate this model. Because the value of the resistance \( R \) is unknown, an assumption must be made. A worst-case assumption would be 10 \( \Omega \).

B.2.2 Forwardly biased diode

In the case of a forwardly biased diode, the diode is modeled by a voltage source and a resistor. The value of the voltage source is equal to the threshold voltage of the diode, the voltage source is thus a DC voltage source. The value of resistor \( R_d \) can be derived from the I-V characteristic curve by piecewise linear modeling. The gradient of the I-V characteristic curve in the forwardly biased zone is equal to \( \frac{1}{R_d} \). In this case, the value of resistor \( R_d \) is not of great importance, since \( R \gg R_d \). The diode in the pulsed thermal plasma torch circuit consists of four parallel RVP50 diodes from the company Electronic Devices Incorporated\(^1\). The threshold voltage is equal to 72 Volt according to the datasheet.

\[ V_T + v_L(t) + v_R(t) = 0 \]

\(^1\)http://www.edidiodes.com
Appendix B  RLC circuit analysis

\[ V_T + R_d i(t) + L \frac{di(t)}{dt} + Ri(t) = 0 \]
\[ L \frac{di(t)}{dt} + (R + R_d)i(t) = -V_T \]

leads to the particular solution

\[ i_p(t) = \frac{-V_T}{R + R_d} \]

The homogeneous equation

\[ L \frac{di_h(t)}{dt} + (R + R_d)i_h(t) = 0 \]

results in

\[ \frac{di_h(t)}{dt} = -\left(\frac{R + R_d}{L}\right)i_h(t) \]
\[ i_h(t) = Ae^{-\left(\frac{R + R_d}{L}\right)t} \]

Substitute to retrieve the current

\[ i(t) = i_h(t) + i_p(t) \]
\[ i(t) = Ae^{-\left(\frac{R + R_d}{L}\right)t} - \frac{V_T}{R + R_d} \]

Filling in the initial condition \( i(0) = I_0 \)

\[ A - \frac{V_T}{R + R_d} = I_0 \]
\[ A = \frac{V_T}{R + R_d} + I_0 \]
\[ A = \frac{V_T + I_0 R + I_0 R_d}{R + R_d} \]

results in the current

\[ i(t) = \frac{V_T + I_0 R + I_0 R_d}{R + R_d} e^{-\left(\frac{R + R_d}{L}\right)t} - \frac{V_T}{R + R_d} \]

The initial current \( I_0 \) can be derived from the reversely biased equation;

\[ I_0 = \frac{V_0}{\omega_d L} e^{-\alpha t_0} \sin(\omega_d t_0) \]

where \( t_0 \) is the moment the diode switches from reversely biased to forwardly biased.
Appendix C

Source code

C.1 Initialization routine

To control the TiePie HandyScope 3 in MATLAB, the instrument has to be initialized. This routine provides this initialization and sets the parameters of the oscilloscope.

hs3setup.m

% hs3setup(Ch1Sens, Ch2Sens, RecordLength, Resolution,
% SampleFrequency, PostSamples)
function hs3setup(Ch1Sens,Ch2Sens,RecordLength,Resolution,SampleFrequency,PostSamples)

if -libisloaded('hs3')
    loadlibrary('hs3','tiepie.h');
end

if ~callDLL('InitInstrument',0);
    pSens = libpointer('doublePtr',Ch1Sens);
    callDLL('SetSensitivity',1,pSens);
    pSens = libpointer('doublePtr',Ch2Sens);
    callDLL('SetSensitivity',2,pSens);
    callDLL('SetResolution',Resolution);
    callDLL('SetSampleFrequency',SampleFrequency);
    callDLL('SetRecordLength',RecordLength);
    % Coupling ChI: DC
    callDLL('SetCoupling',1,1);
    % Coupling Ch2: DC
    callDLL('SetCoupling',2,1);
    % trigger source: Ch1
    callDLL('SetTriggerSource',0);
    % trigger slope: falling
    callDLL('SetTriggerMode',1);
    callDLL('SetTriggerLevel',1,5);
    callDLL('SetTriggerTimeOut',1e6);
    callDLL('SetPostSamples',PostSamples);
else
    error('error initializing instrument');
end

function errorvalue = callDLL(funct,arg1,arg2)
switch nargin
case 1
ervalue = calllib('hs3', funct);
case 2
ervalue = calllib('hs3', funct, arg1);
case 3
ervalue = calllib('hs3', funct, arg1, arg2);
end
if ervalue
switch ervalue
    case 1
        msgbox('E_NO_HARDWARE', ['Error at function ', funct, ' ', 'error'])
    case 2
        msgbox('E_NOT_INITIALIZED', ['Error at function ', funct, ' ', 'error'])
    case 4
        msgbox('E_NOT_SUPPORTED', ['Error at function ', funct, ' ', 'error'])
    case 8
        msgbox('E_NO_GENERATOR', ['Error at function ', funct, ' ', 'error'])
    case 16
        msgbox('E_INVALID_CHANNEL', ['Error at function ', funct, ' ', 'error'])
    case 32
        msgbox('E_INVALID_VALUE', ['Error at function ', funct, ' ', 'error'])
end
end

C.2 Standard measurement routine

The standard measurement routine was developed to provide an easy way to control the TiePie HandyScope 3 and to be able to process the data in MATLAB.

hs3measure.m

function [Channel1, Channel2, t] = hs3measure(SensCh1, SensCh2, RecLen, Resol, SmpFreq, PostSamp)
if -libisloaded('hs3')
    loadlibrary('hs3', 'tiepie.h');
end
hs3setup(SensCh1, SensCh2, RecLen, Resol, SmpFreq, PostSamp);

runs = input('Enter number of measurements: ');
RecordLength = calllib('hs3', 'GetRecordLength');
SampleFrequency = calllib('hs3', 'GetSampleFrequency');
PreSamples = RecordLength - calllib('hs3', 'GetPostSamples');
Channel1 = double(zeros(RecordLength, 1));
ptrChannel1 = libpointer('doublePtr', Channel1);
Channel2 = double(zeros(RecordLength, 1));
ptrChannel2 = libpointer('doublePtr', Channel2);
t = ((1:RecordLength) - PreSamples) / SampleFrequency;
for i = 1:runs
    % Start the measurement
    disp('Waiting for trigger...');
callDLL('StartMeasurement');
disp('Triggered...');
    % Retrieve data from the instrument
    callDLL('GetMeasurement', ptrChannel1, ptrChannel2);
};
C.3 Averaging measurement routine

The averaging measurement routine was developed to investigate the stability of the energy per pulse.

hs3avg.m

function [Emean,t,maxE,stdEgrow] = hs3avg(SensCh1,SensCh2,RecLen,Resol,SmpFreq,PostSamp)

if -libisloaded('hs3')
    loadlibrary('hs3', 'tiepie.h');
end

Ch1Att = 1000;
Ch2Att = 20;

hs3setup(SensCh1,SensCh2,RecLen,Resol,SmpFreq,PostSamp);

runs = input('Enter number of measurements: ');
RecordLength = call1ib('hs3', 'GetRecordLength');
SampleFrequency = call1ib('hs3', 'GetSampleFrequency');
PreSamples = RecordLength - call1ib('hs3', 'GetPostSamples');
Channel1 = double(zeros(RecordLength,1));
ptrChannel1 = libpointer('doublePtr', Channel1);
Channel2 = double(zeros(RecordLength,1));
ptrChannel2 = libpointer('doublePtr', Channel2);

% Retrieve data from local memory
Channel1(:,i) = get(ptrChannel1,'Value');
Channel2(:,i) = get(ptrChanne12,'Va1ue');
end

function ervalue = callDLL(funct,arg1,arg2)
    switch nargin
    case 1
        ervalue = call1ib('hs3', funct);
    case 2
        ervalue = call1ib('hs3', funct, arg1);
    case 3
        ervalue = call1ib('hs3', funct, arg1, arg2);
    end
    if ervalue
        switch ervalue
        case 1
            msgbox('E_NO_HARDWARE', ['Error at function ', funct, 'error'])
        case 2
            msgbox('E_NOT_INITIALIZED', ['Error at function ', funct, 'error'])
        case 4
            msgbox('E_NOT_SUPPORTED', ['Error at function ', funct, 'error'])
        case 8
            msgbox('E_NO_GENERATOR', ['Error at function ', funct, 'error'])
        case 16
            msgbox('E_INVALID_CHANNEL', ['Error at function ', funct, 'error'])
        case 32
            msgbox('E_INVALID_VALUE', ['Error at function ', funct, 'error'])
        end
    end

C.3 Averaging measurement routine
Appendix C  Source code

\[
t = \left(1:RecordLength\right) - PreSamples)/SampleFrequency;
\]
\[
dt = t(2) - t(1);
\]
\[
Emean = zeros(RecordLength,1);
\]
\[
maxE = [];\]
\[
stdEgrow = [];
\]
\[
oldstdE = 1;
\]
\[
disp('Waiting for trigger...');
\]
\[
for i=1:runs
\]
\[
\% Start the measurement
\]
\[
callDLL('StartMeasurement');\]
\[
\% disp(['Triggered... m# ',num2str(i)]);
\]
\[
\% Retrieve data from the instrument
\]
\[
callDLL('GetMeasurement',ptrChannel1,ptrChannel2);\]
\[
\% Retrieve data from local memory
\]
\[
Channel1 = Ch1Att \cdot get(ptrChannel1,'Value');\]
\[
Channel2 = Ch2Att \cdot get(ptrChannel2,'Value');\]
\[
P = Channel1.*Channel2;\]
\[
j = 1;
\]
\[
while t(j) < 0
\]
\[
P(j) = 0;
\]
\[
j = j+1;
\]
\[
end\]
\[
E = cumsum(P)*dt;\]
\[
maxE = [maxE,max(E)];\]
\[
stdE = std(maxE,1);\]
\[
stdEgrow = [stdEgrow,stdE];\]
\[
Emean = (1/i)*E + ((i-1)/i)*Emean;\]
\[
disp([num2str(i), ' std:', num2str(stdE)]);
\]
\[
end\]
\[
disp('The End...');\]

function ervalue = callDLL(funct,arg1,arg2)
switch nargin
  case 1
    ervalue = call1ib('hs3',funct);
  case 2
    ervalue = call1ib('hs3',funct,arg1);
  case 3
    ervalue = call1ib('hs3',funct,arg1,arg2);
end
if ervalue
  switch ervalue
    case 1
      msgbox('E_NO_HARDWARE',['Error at function ','funct','error'])
    case 2
      msgbox('E_NOT_INITIALIZED',['Error at function ','funct','error'])
    case 4
      msgbox('E_NOT_SUPPORTED',['Error at function ','funct','error'])
    case 8
      msgbox('E_NO_GENERATOR',['Error at function ','funct','error'])
    case 16
      msgbox('E_INVALID_CHANNEL',['Error at function ','funct','error'])
    case 32
      msgbox('E_INVALID_VALUE',['Error at function ','funct','error'])
  end
end
C.4 C++ measurement routine

The C++ measurement routine was developed because MATLAB allocates much memory. After a limited amount of samples, the memory of the PC or laptop can become saturated, leading to a slow virtual memory swapping process. The C++ measurement routine overcomes this problem because of the more efficient use of memory compared to MATLAB.

Functions to calculate the energy per pulse and the standard deviation are included, so direct data analysis is possible.

Single shot data is saved to the MATLAB format, which enables the possibility of post-processing the data.

```cpp
#include <cstdlib>
#include <iostream>
#include <vector>  // library for vector class
#include <limits>   // library for sqrt en DBL_MAX
#include "tiepie.h"
#include "c:\matlab71\extern\include\mat.h"

using namespace std;

#define CH1SENS 40
#define CH2SENS 40
#define RECORDLENGTH 50e3
#define TRIGGERLEVEL 5

bool Measure( dword, dword, int );
string MakeFileAndPath( string, int );
vector<double> vproduct( vector<double>, vector<double>, dword, dword );
vector<double> vcumsum( vector<double>, dword );
vector<double> vaverage( vector<double>, dword );
double vmean( vector<double> );
vector<double> vmax( vector<double>, dword );
double stddev( vector<double> );
vector<double> vsqrt( vector<double> );
vector<double> vsum( vector<double>, vector<double>, bool );
vector<double> vsumcast( vector<double>, double, bool );
vector<double> vremoveoffset( vector<double>, dword, dword );
vector<double> vprodcst( vector<double>, double );
void AvgMeas( dword, dword );

int main(int argc, char *argv[]) {
    word wAddress;
    dword dwNumber;
    dword dwCalDate;
    dword dwDay;
    dword dwMonth;
    dword dwYear;
    dword dwSampleFreq;
    double dbSens[20], dbRes[20];
    double dbSens1, dbSens2;
    byte byCurrentRes, byCh1Coup, byCh2Coup;
    dword i, run;
```
SYSTEMTIME st;
GetSystemTime(&st);
cout << st.wDay << "," << st.wMonth << "," << st.wYear << "\t" << st.wHour << ":" << st.wMinute << endl;
cout << "Tiepie HS3 measurement application" << endl;
if ( !OpenDLL( dtHandyscope3 ) ) {
    cout << "Error opening DLL" << endl;
} else {
    wAddress = Ox30B;
    if ( Initlnstrument( wAddress ) != E_NO_ERRORS ) {
        cout << "Hardware not found" << endl;
    } else {
        cout << "Hardware found" << endl;
        if ( GetSerialNumber(&dwNumber) == E_NO_ERRORS ) {
            cout << "Serialnumber: " << dwNumber << endl;
        } else {
            cout << "Error: " << GetSerialNumber(&dwNumber) << endl;
        }
        // Get the calibration date and print to screen
        if ( GetCalibrationDate( &dwCalDate ) == E_NO_ERRORS ) {
            dwDay = dwCalDate >> 24;
            dwMonth = (dwCalDate >> 16) & OXFF;
            dwYear = dwCalDate & OXFFFF;
            cout << "Calibration date: " << dwDay << "," << dwMonth << "\t" << dwYear << endl;
        } // if
        // Get the maximum record length
        cout << "\n\nMaximum Record Length: " << GetMaxRecordLength() << "\nEnter Record Length: ";
        SetRecordLength( RECORDLENGTH );
        cout << "Record Length: " << GetRecordLength() << endl;
        // Retrieve input sensitivities
        GetAvailableSensitivities( dbSens );
        for ( i=0; i < 20; i++ ) {
            cout << dbSens[i] << " ";
        }
        cout << endl;
        // Set the input sensitivities
        dbSens1 = CH1SENS;
        dbSens2 = CH2SENS;
        SetSensitivity( 1, &dbSens1 );
        SetSensitivity( 2, &dbSens2 );
        GetSensitivity( 1, &dbSens1 );
        GetSensitivity( 2, &dbSens2 );
        cout << "Sens1: " << dbSens1 << "\tSens2: " << dbSens2 << endl;
        GetAvailableResolutions( dbRes );
        for ( i=0; i < 20; i++ ) {
            cout << dbRes[i] << " ";
        }
    }
}
cout << endl;
SetResolution( dbRes[0] );
GetResolution( &byCurrentRes );
cout << "Resolution: " << double(byCurrentRes) << endl;
dwSampleFreq = 50e6;
SetSampleFrequency( &dwSampleFreq );
cout << "Sampling Frequency: " << GetSampleFrequency() << endl;
SetCoupling( Ch1, ctDC ); // Channel 1, DC Coupling
SetCoupling( Ch2, ctDC ); // Channel 2, DC Coupling
GetCoupling( Ch1, &byCh1Coup );
GetCoupling( Ch2, &byCh2Coup );
// Check Coupling
cout << "Channel 1 Coupling: " << double(byCh1Coup)
    << "Channel 2 Coupling: " << double(byCh2Coup) << endl;
cout << SetTriggerSource( tsCh1 ) << endl; // Trigger on Channel 1.
cout << SetTriggerMode( tmFalling ) << endl; // Trigger on falling edge.
cout << SetTriggerLevel( Ch1, TRIGGERLEVEL ) << endl;
    // Set to max timeout, using negative overflow.
cout << SetTriggerTimeout( -1 ) << endl;
cout << "Trigger timeout: " << GetTriggerTimeout() << " ms." << endl;
SetPostSamples( 0.8 * RECORDLENGTH );
i = 1;
do {
    cout << "Type #measurements to measure or 0 to quit...

    cin >> run;
    cout << "Runs: " << run << endl;
    // Retrieve data from instrument
    if ( run ) {
        // Measure until user agrees with measurement.
        while (!Measure( RECORDLENGTH, run, i )) {};
        i++;
    }
} while ( run != 0 );
ExitInstrument();
} // if

cout << "The End" << endl;
// system("PAUSE");
return EXIT_SUCCESS;

bool Measure( dword RecLength, dword run, int iMeasurement )
{
    double dbCh1att = 1000; // Attenuation of the voltage probe
    double dbCh2att = 20; // Attenuation of the current probe
    int i, j, status, iPreSamples;
    double *ptrCh1, *ptrCh2, dbStdevEnergy, dBTimeStep;
    MATFile *mfp;
    string strFileName = "";
    char key;

    while ( !strFileName.compare("" ) ) {
strFileName = MakeFileAndPath("d:\my documents\tue\afstudeerstage\measurements\", iMeasurement);
 iMeasurement++;
}

tvCh1.reserve( run * RecLength );
tvCh2.reserve( run * RecLength );

cout << tvCh1.capacity() << "\t" << tvCh2.capacity() << endl;
for (j=0; j < run; j++) {

cout << "Run " << j+1 << " of " << run << endl;

double *dbCh1 = new double[RecLength]; // create Channel1 buffer
double *dbCh2 = new double[RecLength]; // create Channel2 buffer
ptrCh1 = dbCh1; // save original pointer to dbCh1
ptrCh2 = dbCh2; // save original pointer to dbCh2
StartMeasurement();
GetMeasurement( dbChl, dbCh2 );
for (i=0; i < RecLength; i++) {
 if (*dbChl == CHlSENS || *dbChl == -CHlSENS) {

cout << "Channel1 Clipping Alert!!" << endl;
} 

vCh1.push_back(dbCh1att * (*dbChl));
if (*dbCh2 == CH2SENS || *dbCh2 == -CH2SENS) {

cout << "Channel2 Clipping Alert!!" << endl;
} 

vCh2.push_back(dbCh2att * (*dbCh2));
*dbChl++;
*dbCh2++;
}
delete [] ptrCh1; // delete Channel1 buffer
delete [] ptrCh2; // delete Channel2 buffer
}

cout << "Measurement OK? [press d to delete data]: ";
cin >> key;
if (key == 'd') {

vCh1.clear();
vCh2.clear();
cout << "\nRestarting measurement..." << endl;
return false;
}
// Remove the offset on the two channels
// using the last 2000 samples of the Record length
vCh1 = vremoveoffset(vCh1, run, 2000);
vCh2 = vremoveoffset(vCh2, run, 2000);

vPower.reserve( run * RecLength );
vPower = vproduct(vChl, vCh2, run, (0.2) * RecLength);

// Save to strFilename
mfp = matOpen( strFileName.begin(), "w"); // Create a mat file pointer

// Save Channel1 to mat-file
CA

C++

measurement routine

mxCh1 = mxCreateDoubleMatrix( RecLength, run, mxREAL );
memcpy((void *)(mxGetPr(mxC1)), vCh1.begin(), run * RecLength * sizeof(double));
// cout << "Writing Channel1 to " << strFileName.begin() << endl;
status = matPutVariable(mfp, "Channel1", mxCh1);
cout << "Status: " << status << endl;
mxDestroyArray(mxC1);

// Clear Channel 1
vCh1.clear();

mxCh2 = mxCreateDoubleMatrix( RecLength, run, mxREAL );
memcpy((void *)(mxGetPr(mxC1)), vCh2.begin(), run * RecLength * sizeof(double));
status = matPutVariable(mfp, "Channel2", mxCh2);
cout << "Status: " << status << endl;
mxDestroyArray(mxC2);

// Calculate Energy
vEnergy.reserve( run * RecLength );
vEnergy = vprodct( vcumsum( vPower, run ), 1/(double)GetSampleFrequency() );

// Clear Power
vPower.clear();

vAverageEnergy.reserve( RecLength );
vAverageEnergy = vaverage(vEnergy, run);
vMaxEnergy = vmax(vEnergy, run);
dbStdevEnergy = stdev(vMaxEnergy);

mxEnergy = mxCreateDoubleMatrix( RecLength, run, mxREAL );
memcpy((void *)(mxGetPr(mxEnergy)), vEnergy.begin(), run * RecLength * sizeof(double));
status = matPutVariable(mfp, "E", mxEnergy);
cout << "Status: " << status << endl;
mxDestroyArray(mxEnergy);

vEnergy.clear();

mxAverageEnergy = mxCreateDoubleMatrix( RecLength, 1, mxREAL );
memcpy((void *)(mxGetPr(mxAverageEnergy)), vAverageEnergy.begin(), RecLength * sizeof(double));
status = matPutVariable(mfp, "avgE", mxAverageEnergy);
cout << "Status: " << status << endl;
mxDestroyArray(mxAverageEnergy);

vAverageEnergy.clear();

mxMaxEnergy = mxCreateDoubleMatrix( 1, run, mxREAL );
memcpy((void *)(mxGetPr(mxMaxEnergy)), vMaxEnergy.begin(), run * sizeof(double));
status = matPutVariable(mfp, "maxE", mxMaxEnergy);
cout << "Status: " << status << endl;
mxDestroyArray(mxMaxEnergy);

cout << "Mean Energy per pulse: " << vaverage(vMaxEnergy, vMaxEnergy.size())[0] << endl;

vMaxEnergy.clear();

mxStdevEnergy = mxCreateDoubleMatrix( 1, 1, mxREAL );
memcpy((void *)(mxGetPr(mxStdevEnergy)), &dbStdevEnergy, sizeof(double));
status = matPutVariable(mfp, "stdE", mxStdevEnergy);
cout << "Status: " << status << endl;
mxDestroyArray(mxStdevEnergy);

vTime.reserve( RecLength );
iPreSamples = RecLength - GetPostSamples();
dbTimeStep = 1 / (double)GetSampleFrequency();
// Create time vector
for (i=0; i < RecLength; i++) {
    vTime.push_back((i - iPreSamples) * dbTimeStep);
}

mxTime = mxCreateDoubleMatrix( RecLength, 1, mxREAL );
memcpy((void *)(mxGetPr(mxTime)), vTime.begin(), RecLength * sizeof(double));
status = matPutVariable(mfp, "t", mxTime);
cout << "Status: " << status << endl;
mxDestroyArray(mxTime);

// Clear time vector
vTime.clear();

matClose(mfp);

cout << "Standard Deviation Energy: " << dbStdevEnergy << endl;
return true;

string MakeFileAndPath( string strFilePath, int iMeasurement )
{
    SYSTEMTIME st;
    char chNumber[4];
    FILE *check;
    // Create path based on date
    GetSystemTime(&st);
    itoa( st.wYear, chNumber, 10 );
    strFilePath.append( chNumber );
    strFilePath.append( "_,, ");
    itoa( st.wMonth, chNumber, 10 );
    strFilePath.append( chNumber );
    strFilePath.append( "_,, ");
    itoa( st.wDay, chNumber, 10 );
    strFilePath.append( chNumber );
    CreateDirectory( strFilePath.begin(), NULL );
    strFilePath.append( "\measurement_" );
    itoa( iMeasurement, chNumber, 10 );
    strFilePath.append( chNumber );
    strFilePath.append( ".mat" );
cout << strFilePath.begin() << endl;
    // Check if filename already exists.
    check = fopen(strFilePath.begin(), "r");
    if ( check != NULL ) {
        cout << "File already exists, incrementing to " << iMeasurement + 1 << endl;
        fclose(check);
        return "";
    }
}
else {
    return strFilePath;
}
}

vector <double> vproduct(vector <double> v1, vector <double> v2, dword dwChunks, dword dwStart)
{
    vector <double> vResult;
    dword dwRecLength;
    int i, j;
    if (v1.size() == v2.size()) {
        dwRecLength = v1.size() / dwChunks;
        for (j=0; j < dwChunks; j++) {
            vResult.insert( vResult.end(), dwStart+i, 0 );
            for (i=dwStart+i; i < dwRecLength; i++) {
                vResult.push_back( v1[i+j*dwRecLength] * v2[i+j*dwRecLength] );
            }
        }
        return vResult;
    } else {
        return NULL;
    }
}

vector <double> vcumsum( vector <double> v1, dword dwChunks )
{
    int i, j;
    vector <double> vResult;
    double sum;
    dword dwRecLength = v1.size() / dwChunks;
    for (j=0; j < dwChunks; j++) {
        sum = 0;
        for (i=0; i < dwRecLength; i++) {
            vResult.push_back( v1[i+j*dwRecLength] + sum );
            sum += v1[i+j*dwRecLength];
        }
        return vResult;
    }
}

vector <double> vaverage( vector <double> v1, dword dwChunks )
{
    vector <double> vResult;
    double mean;
    int i, j;
    dword dwRecLength = v1.size() / dwChunks;
    for (j=0; j < dwRecLength; j++) {
        mean = 0;
        for (i=0; i < dwChunks; i++) {
            mean += v1[i+j*dwRecLength];
        }
        vResult.push_back( mean / ((double)dwChunks) );
    }
    return vResult;
}
Appendix C  Source code

double vmean( vector <double> vl )
{
    double dbSum = 0;
    int i;
    for (i=0; i < vl.size(); i++) {
        dbSum += vl[i];
    }
    return (dbSum/vl.size());
}

vector <double> vmax( vector <double> vl, dword dwChunks )
{
    dword dwRecLength = vl.size() / dwChunks;
    vector <double> vResult;
    double max;
    int i, j;
    for (j=0; j < dwChunks; j++) {
        max = -DBL_MAX;
        for (i=0; i < dwRecLength; i++) {
            if (vl[i+j*dwRecLength] > max) {
                max = vl[i+j*dwRecLength];
            }
        }
        vResult.push_back( max );
    }
    return vResult;
}

double stdev( vector <double> vl )
{
    // Standard deviation as sigma = sqrt( E(X^2) - mu^2 )
    // Notice that Matlab uses a different approach to calculate the standard deviation!
    double dbResult;
    dbResult = sqrt( vmean(vproduct(vl,vl,1,1)) - vmean(vl)*vmean(vl) );
    return dbResult;
}

vector <double> vsqrt( vector <double> vl )
{
    vector <double> vResult;
    int i;
    for (i=0; i < vl.size(); i++) {
        vResult.push_back( sqrt(vl[i]) );
    }
    return vResult;
}

vector <double> vsum( vector <double> vl, vector <double> v2, bool bSign )
{
    vector <double> vResult;
    int i;
    if (bSign) {
        for (i=0; i<v1.size(); i++) {
            vResult.push_back( v1[i] - v2[i] );
        }
    }
}
```cpp
else {
    for (i=0; i<vl.size(); i++) {
        vResult.push_back( v1[i] + v2[i] );
    }
    return vResult;
}

vector<double> vsumcst( vector<double> v1, double dbCst, bool bSign )
{
    vector<double> vResult;
    int i;
    if (bSign) {
        for (i=0; i<vl.size(); i++) {
            vResult.push_back( v1[i] - dbCst );
        }
    } else {
        for (i=0; i<vl.size(); i++) {
            vResult.push_back( v1[i] + dbCst );
        }
    }
    return vResult;
}

vector<double> vremoveoffset(vector<double> v1, dword dwChunks, dword dwNumberOfSamples)
{
    vector<double> vResult;
    dword dwRecLength = v1.size() / dwChunks;
    int i, j;
    double dbMean;
    for (j=0; j < dwChunks; j++) {
        dbMean = 0;
        for (i=dwRecLength - dwNumberOfSamples; i < dwRecLength; i++) {
            dbMean = dbMean + v1[i + j*dwRecLength];
        }
        dbMean = dbMean / dwNumberOfSamples;
        for (i=0; i < dwRecLength; i++) {
            vResult.push_back( v1[i + j*dwRecLength] - dbMean );
        }
    }
    return vResult;
}

vector<double> vprodcst( vector<double> v1, double dbCst )
{
    vector<double> vResult;
    int i;
    for (i=0; i < vl.size(); i++) {
        vResult.push_back( v1[i] * dbCst );
    }
    return vResult;
}
```

Appendix C  Source code

C.5  Matlab compression routine

The C++ measurement routine does not provide the v6 compression used in MATLAB. This routine compresses the data generated by the C++ measurement routine by loading the data to workspace and saving it to the same file.

resave.m

function resave()
directory = uigetdir;
disp(directory);
if directory ~= 0
    files = dir(fullfile(directory, '*.mat'));
    for i=1:length(files)
        savethis(fullfile(directory, '/', files(i).name));
        disp(fullfile(files(i).name, ' resaved ... '));
    end
    disp('Done ... ');
end

function savethis(filename)
load(filename);
save(filename);

C.6  Pulsed thermal plasma model

This routine is used for comparison the pulsed thermal plasma model to a measured current.

ptpmodel.m

% [Rp,Imodel,alpha*t] = ptpmodel(t,I,L_tr,C_tr,L_th,C_th)
% t: time, I: current, V: voltage
% L_tr: inductance transient mode, C_tr: capacitance transient mode
% L_th: inductance thermal mode, C_th: capacitance thermal mode
% Rp: resistance of the plasma, Imodel: model of the plasma current
% alphat: alpha*t, debugging purposes
% plot: switch plots on or off [0,1]
function [Rp,Imodel,alphat] = detR(t,I,V,L_tr,C_tr,L_th,C_th,plotmdl)
% find index of time T using linear extrapolation.
dt=t(2)-t(1);
indexT=1;
T = 0-dt;
while abs(t(indexT) - T) > dt
    indexT = ceil(indexT + (T - t(indexT))/dt);
end
% Voltage
V0 = max(V);
% Erase data before t=0
I = I(indexT:length(I));
V = V(indexT:length(V));

%%%%%%%%%%%%%%%%%%%%%% Transient mode %%%%%%%%%%%%%%%%%%%%%%%
% Resonant frequency
w0_tr = 1/sqrt(L_tr*C_tr);

68
% Damped frequency, approximate it by the resonant frequency
wd_tr = w0_tr;
% Sampling frequency in radians per second
ws = 2*pi*(1/dt);
% 5th order Butterworth filter, cutoff frequency @ 0.75*w0,
% lowpass
[a,b] = butter(15,0.75*wd_tr/(0.5*ws), 'low');
% Flip the time axis, so filtering starts at t_end
I2filt = filter(a,b,flipud(I.*I));
% Flip the time axis back
I2filt = flipud(I2filt);

alpha_tr = 1e-3/(2*L_tr);
alphold = 1e-20/(2*L_tr);
while abs((alphold-alpha_tr)/alpha_tr) > 1e-6
    alphold = alpha_tr;
    % Calculate alpha*t
    alphat = log(VO./(wd_tr*L_tr*sqrt(2*abs(I2filt))));
    % Find alpha*t = 2, since exp(-2) = 0.14
    i = 1;
    while alphat(i) < 2
        i = i + 1;
    end
    % Approximate alpha by linear
    alpha_tr = (alphat(i)-alphat(1))/(t(i)-t(1));
    % Calculate the damped frequency
    wd_tr = sqrt(w0_tr*w0_tr-alpha_tr*alpha_tr);
end
end_tr = i;
% Calculate the current according to RLC circuit
Itrmdl = (VO/(wd_tr*L_tr))*exp(-alpha_tr*t).*sin(wd_tr*t);
Rp = 2*alpha_tr*L_tr;

% include DC resistance of coils
R_th = Rp + 2;
% Threshold voltage of RVP-50 diode
VT = 72;
% Diode resistance
Rd = 5e-4;
% Resonant frequency of thermal mode
w0_th = 1/sqrt(L_th*C_th);
% Damping coefficient
alpha_th = R_th/(2*L_th);
% gamma = 1/(2*Rd);
% beta = sqrt((gamma-alpha)*(gamma-alpha)-w0*w0);
% Damped frequency thermal mode
wd_th = sqrt(w0_th*w0_th-alpha_th*alpha_th);
% Reverse biased diode model
Ithmdl1 = (VO/(wd_th*L_th))*exp(-alpha_th*t).*sin(wd_th*t);
% Voltage over capacitor, same as voltage over diode
VC_th = -(1/C_th)*cumsum(Ithmdl1)*dt + V0;
% Find moment of switching to forward biased diode
i=1;
while VC_th(i) > -VT
    i = i + 1;
end
% Set t=0 at the switching point
\[ t2 = t(i:length(t)) - t(i); \]
\[ I2 = I(i:length(I)); \]
\[ I0 = \left( \frac{V0}{(wd_th*L_th)} \right) \exp(-\alpha_th*t(i)) \cdot \sin(wd_th*t(i)); \]

% Forward biased diode model
\[ Ithmdl2 = \left( \frac{VT+I0*R_th+I0*Rd}{R_th+Rd} \right) \cdot \exp\left(\frac{-R_th+Rd}{L_th}t2\right) - \frac{VT}{R_th+Rd}; \]

% Join the two thermal models
\[ Ithmdl = [Ithmdl1(1:i-1); Ithmdl2]; \]
% Remove the negative current, arc is extinguished.
\[ i = \text{length}(Ithmdl); \]
while Ithmdl(i) < 0
    Ithmdl(i) = 0;
    i = i - 1;
end
% Add the transient model to the thermal model
\[ I_{\text{model}} = I_{\text{trmdl}} + I_{\text{thmdl}}; \]

if plotmdl
    plotmodel(t,I,V,I_{\text{model}},Ithmdl1,Rp,end_tr)
end

function plotmodel(t,I,V,I_{\text{model}},Ithmdl1,Rp,end_tr)
    close all
    plot(t(1:end_tr),I(1:end_tr),t(1:end_tr),I_{\text{model}}(1:end_tr),'r')
    grid on
    legend('I_{\text{meas}}','I_{\text{model}}','Location','Best')
    xlabel('time [s]')
    ylabel('I [A]')
    % Tight x-axis
    set(gca,'XLimMode','manual');
    set(gca,'XLim',[t(1) t(end_tr)]);
    figure
    plot(t(1:end_tr),V(1:end_tr),t(1:end_tr),R_{\text{p}}\cdot I_{\text{model}}(1:end_tr),'r')
    grid on
    legend('V_{\text{meas}}','V_{\text{model}}','Location','Best')
    xlabel('time [s]')
    ylabel('V [V]')
    % Tight x-axis
    set(gca,'XLimMode','manual');
    set(gca,'XLim',[t(1) t(end_tr)]);
    figure
    plot(t,I,t,I_{\text{model}},'r')
    grid on
    legend('I_{\text{meas}}','I_{\text{model}}','Location','Best')
    xlabel('time [s]')
    ylabel('I [A]')
    figure
    plot(t,V,t,R_{\text{p}}\cdot I_{\text{model}},'r')
    grid on
    legend('V_{\text{meas}}','V_{\text{model}}','Location','Best')
    xlabel('time [s]')
    ylabel('V [V]')
Appendix D

Measurement data

All measurements are performed with one pulse source. The repetition rate was increased stepwise with 10 pulses per second. Because of a difference between the potentiometer reading and the actual pulse repetition rate, a correction on the potentiometer reading has to be performed.

<table>
<thead>
<tr>
<th>Measurement #</th>
<th>Potentiometer reading (pulses/s)</th>
<th>Pulse repetition rate (pulses/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>13.3478</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>23.9898</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>34.6318</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>45.2738</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>55.9158</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>66.5578</td>
</tr>
<tr>
<td>7</td>
<td>70</td>
<td>77.1998</td>
</tr>
<tr>
<td>8</td>
<td>80</td>
<td>87.8418</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
<td>98.4838</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>109.1258</td>
</tr>
</tbody>
</table>

D.1 Heat balance

D.1.1 Configuration 1

<table>
<thead>
<tr>
<th></th>
<th>( C_L )</th>
<th>( C_{th} )</th>
<th>( C_{tr} )</th>
<th>( L_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.2 ( \mu ) F</td>
<td>3.3 nF</td>
<td>0 F</td>
<td>1.5 mH</td>
</tr>
</tbody>
</table>
flow = 2.75 l/s, Re ≈ 8000

Table D.3: First data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>EPP$^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.6</td>
<td>21.4</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>2.664255</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20.2</td>
<td>22.6</td>
<td>2.4</td>
<td>0.5416</td>
<td>6.771993</td>
<td>7.992765</td>
<td>0.786845</td>
<td>0.057524</td>
</tr>
<tr>
<td>2</td>
<td>20.2</td>
<td>23.5</td>
<td>3.3</td>
<td>0.5005</td>
<td>13.21490</td>
<td>10.99005</td>
<td>0.630031</td>
<td>0.045611</td>
</tr>
<tr>
<td>3</td>
<td>20.1</td>
<td>24.5</td>
<td>4.4</td>
<td>0.5466</td>
<td>17.69824</td>
<td>14.65340</td>
<td>0.677421</td>
<td>0.042260</td>
</tr>
<tr>
<td>4</td>
<td>20.0</td>
<td>25.7</td>
<td>5.7</td>
<td>0.5384</td>
<td>21.31038</td>
<td>18.98282</td>
<td>0.765757</td>
<td>0.062406</td>
</tr>
<tr>
<td>5</td>
<td>20.0</td>
<td>26.7</td>
<td>6.7</td>
<td>0.5642</td>
<td>28.73082</td>
<td>22.31314</td>
<td>0.683895</td>
<td>0.077225</td>
</tr>
<tr>
<td>6</td>
<td>20.0</td>
<td>27.7</td>
<td>7.7</td>
<td>0.5106</td>
<td>36.76467</td>
<td>25.64345</td>
<td>0.625035</td>
<td>0.078509</td>
</tr>
<tr>
<td>7</td>
<td>19.9</td>
<td>28.8</td>
<td>8.9</td>
<td>0.5354</td>
<td>33.03673</td>
<td>29.63984</td>
<td>0.816533</td>
<td>0.087196</td>
</tr>
<tr>
<td>8</td>
<td>19.9</td>
<td>29.5</td>
<td>9.6</td>
<td>0.5328</td>
<td>43.64789</td>
<td>31.97106</td>
<td>0.671437</td>
<td>0.075858</td>
</tr>
<tr>
<td>9</td>
<td>19.9</td>
<td>30.5</td>
<td>10.6</td>
<td>0.5164</td>
<td>55.86198</td>
<td>35.30138</td>
<td>0.584246</td>
<td>0.093344</td>
</tr>
<tr>
<td>10</td>
<td>19.9</td>
<td>30.6</td>
<td>10.7</td>
<td>0.4762</td>
<td>47.95577</td>
<td>35.63441</td>
<td>0.687512</td>
<td>0.096098</td>
</tr>
</tbody>
</table>

Table D.4: Reproduction data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>EPP$^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18.7</td>
<td>19.5</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>2.664255</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>18.8</td>
<td>20.6</td>
<td>1.8</td>
<td>0.5450</td>
<td>8.029503</td>
<td>5.994574</td>
<td>0.414760</td>
<td>0.117294</td>
</tr>
<tr>
<td>2</td>
<td>18.8</td>
<td>21.5</td>
<td>2.7</td>
<td>0.5933</td>
<td>14.28804</td>
<td>8.991861</td>
<td>0.442860</td>
<td>0.055552</td>
</tr>
<tr>
<td>3</td>
<td>18.8</td>
<td>22.5</td>
<td>3.7</td>
<td>0.5874</td>
<td>19.30581</td>
<td>12.32218</td>
<td>0.500260</td>
<td>0.052870</td>
</tr>
<tr>
<td>4</td>
<td>18.9</td>
<td>23.3</td>
<td>4.4</td>
<td>0.6119</td>
<td>28.75860</td>
<td>14.65340</td>
<td>0.416889</td>
<td>0.039003</td>
</tr>
<tr>
<td>5</td>
<td>19.0</td>
<td>24.4</td>
<td>5.4</td>
<td>0.5739</td>
<td>29.12078</td>
<td>17.98372</td>
<td>0.526066</td>
<td>0.034254</td>
</tr>
<tr>
<td>6</td>
<td>19.1</td>
<td>25.2</td>
<td>6.1</td>
<td>0.5635</td>
<td>39.72176</td>
<td>20.31494</td>
<td>0.444358</td>
<td>0.113523</td>
</tr>
<tr>
<td>7</td>
<td>19.1</td>
<td>26.1</td>
<td>7.0</td>
<td>0.5375</td>
<td>43.08274</td>
<td>23.31223</td>
<td>0.479263</td>
<td>0.091136</td>
</tr>
<tr>
<td>8</td>
<td>19.1</td>
<td>26.7</td>
<td>7.6</td>
<td>0.5196</td>
<td>43.25225</td>
<td>25.31042</td>
<td>0.523584</td>
<td>0.100405</td>
</tr>
<tr>
<td>9</td>
<td>19.2</td>
<td>27.5</td>
<td>8.3</td>
<td>0.5033</td>
<td>51.26948</td>
<td>27.64165</td>
<td>0.487179</td>
<td>0.111820</td>
</tr>
<tr>
<td>10</td>
<td>19.3</td>
<td>28.0</td>
<td>8.7</td>
<td>0.5117</td>
<td>49.38543</td>
<td>28.97377</td>
<td>0.532739</td>
<td>0.103065</td>
</tr>
</tbody>
</table>

$^1$EPP: Energy Per Pulse
flow = 3.5 ℓ/s, Re ≈ 10000

D.1 Heat balance

Table D.5: First data

<table>
<thead>
<tr>
<th>#</th>
<th>T_{in} [°C]</th>
<th>T_{out} [°C]</th>
<th>ΔT [°C]</th>
<th>EPP (^1) [J/pulse]</th>
<th>Power [W]</th>
<th>(\dot{Q}) [W]</th>
<th>(\eta)</th>
<th>std EPP (^1) [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>19.8</td>
<td>20.6</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>3.39087</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20.0</td>
<td>21.7</td>
<td>1.7</td>
<td>0.5001</td>
<td>6.317380</td>
<td>7.205599</td>
<td>0.603847</td>
<td>0.049053</td>
</tr>
<tr>
<td>2</td>
<td>20.1</td>
<td>22.8</td>
<td>2.7</td>
<td>0.5387</td>
<td>13.20766</td>
<td>11.44419</td>
<td>0.609746</td>
<td>0.085680</td>
</tr>
<tr>
<td>3</td>
<td>20.3</td>
<td>23.8</td>
<td>3.5</td>
<td>0.5234</td>
<td>19.46931</td>
<td>14.83506</td>
<td>0.587807</td>
<td>0.051746</td>
</tr>
<tr>
<td>4</td>
<td>20.5</td>
<td>24.5</td>
<td>4.0</td>
<td>0.5399</td>
<td>21.25075</td>
<td>16.95435</td>
<td>0.638259</td>
<td>0.062045</td>
</tr>
<tr>
<td>5</td>
<td>20.3</td>
<td>25.4</td>
<td>5.1</td>
<td>0.5171</td>
<td>32.45504</td>
<td>21.61680</td>
<td>0.561575</td>
<td>0.092310</td>
</tr>
<tr>
<td>6</td>
<td>20.7</td>
<td>26.3</td>
<td>5.6</td>
<td>0.4814</td>
<td>37.29999</td>
<td>23.73609</td>
<td>0.545448</td>
<td>0.072698</td>
</tr>
<tr>
<td>7</td>
<td>20.5</td>
<td>27.3</td>
<td>6.8</td>
<td>0.5297</td>
<td>37.72777</td>
<td>28.82240</td>
<td>0.674080</td>
<td>0.089807</td>
</tr>
<tr>
<td>8</td>
<td>20.7</td>
<td>27.8</td>
<td>7.1</td>
<td>0.4736</td>
<td>41.83835</td>
<td>30.09397</td>
<td>0.638245</td>
<td>0.108127</td>
</tr>
<tr>
<td>9</td>
<td>20.6</td>
<td>28.7</td>
<td>8.1</td>
<td>0.4970</td>
<td>58.14267</td>
<td>34.33256</td>
<td>0.532168</td>
<td>0.095752</td>
</tr>
<tr>
<td>10</td>
<td>20.8</td>
<td>29.6</td>
<td>8.8</td>
<td>0.4645</td>
<td>53.22895</td>
<td>37.29957</td>
<td>0.637035</td>
<td>0.113255</td>
</tr>
</tbody>
</table>

Table D.6: Reproduction data

<table>
<thead>
<tr>
<th>#</th>
<th>T_{in} [°C]</th>
<th>T_{out} [°C]</th>
<th>ΔT [°C]</th>
<th>EPP (^1) [J/pulse]</th>
<th>Power [W]</th>
<th>(\dot{Q}) [W]</th>
<th>(\eta)</th>
<th>std EPP (^1) [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.1</td>
<td>21.6</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>2.119294</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20.8</td>
<td>22.4</td>
<td>1.6</td>
<td>0.5757</td>
<td>6.769884</td>
<td>6.781740</td>
<td>0.688704</td>
<td>0.079039</td>
</tr>
<tr>
<td>2</td>
<td>20.9</td>
<td>23.0</td>
<td>2.1</td>
<td>0.5728</td>
<td>12.88778</td>
<td>8.901034</td>
<td>0.526215</td>
<td>0.075612</td>
</tr>
<tr>
<td>3</td>
<td>20.7</td>
<td>23.6</td>
<td>2.9</td>
<td>0.5814</td>
<td>20.71771</td>
<td>12.29190</td>
<td>0.491010</td>
<td>0.035433</td>
</tr>
<tr>
<td>4</td>
<td>20.8</td>
<td>24.4</td>
<td>3.6</td>
<td>0.5748</td>
<td>23.80972</td>
<td>15.25892</td>
<td>0.551860</td>
<td>0.061430</td>
</tr>
<tr>
<td>5</td>
<td>20.7</td>
<td>25.0</td>
<td>4.3</td>
<td>0.5634</td>
<td>32.93217</td>
<td>18.22593</td>
<td>0.489085</td>
<td>0.030059</td>
</tr>
<tr>
<td>6</td>
<td>20.6</td>
<td>25.7</td>
<td>5.1</td>
<td>0.5819</td>
<td>39.64302</td>
<td>21.61680</td>
<td>0.491827</td>
<td>0.044199</td>
</tr>
<tr>
<td>7</td>
<td>20.6</td>
<td>26.3</td>
<td>5.7</td>
<td>0.5578</td>
<td>45.56494</td>
<td>24.15995</td>
<td>0.483720</td>
<td>0.059327</td>
</tr>
<tr>
<td>8</td>
<td>20.6</td>
<td>26.7</td>
<td>6.1</td>
<td>0.5556</td>
<td>47.01284</td>
<td>25.85538</td>
<td>0.504885</td>
<td>0.040104</td>
</tr>
<tr>
<td>9</td>
<td>20.7</td>
<td>27.3</td>
<td>6.6</td>
<td>0.5312</td>
<td>53.35734</td>
<td>27.97468</td>
<td>0.484570</td>
<td>0.039787</td>
</tr>
<tr>
<td>10</td>
<td>20.5</td>
<td>27.8</td>
<td>7.3</td>
<td>0.5334</td>
<td>47.05614</td>
<td>30.94169</td>
<td>0.612511</td>
<td>0.050545</td>
</tr>
</tbody>
</table>

\(^1\)EPP: Energy Per Pulse
flow = 4.4 \text{ l/s}, \text{ Re} \approx 13000

<table>
<thead>
<tr>
<th>#</th>
<th>T\text{in} [\text{°C}]</th>
<th>T\text{out} [\text{°C}]</th>
<th>\Delta T [\text{°C}]</th>
<th>\text{EPP}\textsuperscript{1} [\text{J/pulse}]</th>
<th>Power [\text{W}]</th>
<th>\dot{Q} [\text{W}]</th>
<th>\eta</th>
<th>\text{std EPP}\textsuperscript{1} [\text{J/pulse}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.6</td>
<td>22.1</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>2.664255</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>21.4</td>
<td>22.8</td>
<td>1.4</td>
<td>0.5288</td>
<td>6.716439</td>
<td>7.459914</td>
<td>0.714018</td>
<td>0.053431</td>
</tr>
<tr>
<td>2</td>
<td>21.2</td>
<td>23.6</td>
<td>2.4</td>
<td>0.5496</td>
<td>12.59481</td>
<td>12.78842</td>
<td>0.803836</td>
<td>0.041010</td>
</tr>
<tr>
<td>3</td>
<td>21.0</td>
<td>24.2</td>
<td>3.2</td>
<td>0.5720</td>
<td>19.03270</td>
<td>17.05123</td>
<td>0.755908</td>
<td>0.039246</td>
</tr>
<tr>
<td>4</td>
<td>21.3</td>
<td>24.9</td>
<td>3.6</td>
<td>0.5633</td>
<td>29.65049</td>
<td>19.18264</td>
<td>0.557103</td>
<td>0.043864</td>
</tr>
<tr>
<td>5</td>
<td>21.3</td>
<td>26.0</td>
<td>4.7</td>
<td>0.5955</td>
<td>31.10943</td>
<td>25.04400</td>
<td>0.719388</td>
<td>0.056655</td>
</tr>
<tr>
<td>6</td>
<td>21.2</td>
<td>26.6</td>
<td>5.4</td>
<td>0.5595</td>
<td>32.62364</td>
<td>28.77395</td>
<td>0.800331</td>
<td>0.072837</td>
</tr>
<tr>
<td>7</td>
<td>21.0</td>
<td>27.2</td>
<td>6.2</td>
<td>0.5300</td>
<td>30.31536</td>
<td>33.03676</td>
<td>1.001885</td>
<td>0.080572</td>
</tr>
<tr>
<td>8</td>
<td>21.3</td>
<td>27.8</td>
<td>6.5</td>
<td>0.5190</td>
<td>41.84696</td>
<td>34.63532</td>
<td>0.764000</td>
<td>0.101472</td>
</tr>
<tr>
<td>9</td>
<td>21.3</td>
<td>28.6</td>
<td>7.3</td>
<td>0.5137</td>
<td>58.91252</td>
<td>38.89812</td>
<td>0.615045</td>
<td>0.077335</td>
</tr>
<tr>
<td>10</td>
<td>21.2</td>
<td>29.4</td>
<td>8.2</td>
<td>0.5043</td>
<td>65.47657</td>
<td>43.69378</td>
<td>0.626629</td>
<td>0.085167</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>T\text{in} [\text{°C}]</th>
<th>T\text{out} [\text{°C}]</th>
<th>\Delta T [\text{°C}]</th>
<th>\text{EPP}\textsuperscript{1} [\text{J/pulse}]</th>
<th>Power [\text{W}]</th>
<th>\dot{Q} [\text{W}]</th>
<th>\eta</th>
<th>\text{std EPP}\textsuperscript{1} [\text{J/pulse}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.3</td>
<td>21.0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>3.729957</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20.4</td>
<td>21.9</td>
<td>1.5</td>
<td>0.5608</td>
<td>6.898370</td>
<td>7.992765</td>
<td>0.617944</td>
<td>0.043597</td>
</tr>
<tr>
<td>2</td>
<td>20.9</td>
<td>22.8</td>
<td>1.9</td>
<td>0.5663</td>
<td>12.41237</td>
<td>10.12417</td>
<td>0.515148</td>
<td>0.052461</td>
</tr>
<tr>
<td>3</td>
<td>21.2</td>
<td>23.5</td>
<td>2.3</td>
<td>0.5481</td>
<td>17.90606</td>
<td>12.25557</td>
<td>0.476130</td>
<td>0.090601</td>
</tr>
<tr>
<td>4</td>
<td>20.7</td>
<td>24.5</td>
<td>3.8</td>
<td>0.5944</td>
<td>28.36277</td>
<td>20.24834</td>
<td>0.582397</td>
<td>0.028546</td>
</tr>
<tr>
<td>5</td>
<td>20.9</td>
<td>25.0</td>
<td>4.1</td>
<td>0.5732</td>
<td>33.11736</td>
<td>21.84689</td>
<td>0.547052</td>
<td>0.086108</td>
</tr>
<tr>
<td>6</td>
<td>20.9</td>
<td>25.4</td>
<td>4.5</td>
<td>0.5900</td>
<td>39.77694</td>
<td>23.97830</td>
<td>0.509047</td>
<td>0.040098</td>
</tr>
<tr>
<td>7</td>
<td>20.9</td>
<td>26.0</td>
<td>5.1</td>
<td>0.5701</td>
<td>43.38135</td>
<td>27.17540</td>
<td>0.540450</td>
<td>0.046783</td>
</tr>
<tr>
<td>8</td>
<td>20.9</td>
<td>26.5</td>
<td>5.6</td>
<td>0.5332</td>
<td>48.41102</td>
<td>29.83966</td>
<td>0.539334</td>
<td>0.089509</td>
</tr>
<tr>
<td>9</td>
<td>20.9</td>
<td>27.1</td>
<td>6.2</td>
<td>0.5406</td>
<td>50.33409</td>
<td>33.03676</td>
<td>0.582246</td>
<td>0.048849</td>
</tr>
<tr>
<td>10</td>
<td>20.9</td>
<td>27.6</td>
<td>6.7</td>
<td>0.5290</td>
<td>53.67418</td>
<td>35.70102</td>
<td>0.595651</td>
<td>0.054213</td>
</tr>
</tbody>
</table>

\textsuperscript{1}\text{EPP}: Energy Per Pulse
flow = 5.0 ℓ/s, Re ≈ 15000

Table D.9: First data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>$EPP^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.9</td>
<td>21.3</td>
<td>0.4</td>
<td>0</td>
<td>2.42205</td>
<td>–</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21.0</td>
<td>22.1</td>
<td>1.1</td>
<td>0.5516</td>
<td>6.032298</td>
<td>6.660638</td>
<td>0.702649</td>
<td>0.113075</td>
</tr>
<tr>
<td>2</td>
<td>21.1</td>
<td>22.8</td>
<td>1.7</td>
<td>0.5971</td>
<td>12.18435</td>
<td>10.29371</td>
<td>0.646047</td>
<td>0.062979</td>
</tr>
<tr>
<td>3</td>
<td>21.2</td>
<td>23.5</td>
<td>2.3</td>
<td>0.5818</td>
<td>23.23918</td>
<td>13.92679</td>
<td>0.495058</td>
<td>0.089059</td>
</tr>
<tr>
<td>4</td>
<td>21.2</td>
<td>24.0</td>
<td>2.8</td>
<td>0.5500</td>
<td>26.55634</td>
<td>16.95435</td>
<td>0.547225</td>
<td>0.140573</td>
</tr>
<tr>
<td>5</td>
<td>21.2</td>
<td>24.6</td>
<td>3.4</td>
<td>0.5282</td>
<td>28.60932</td>
<td>20.58743</td>
<td>0.634946</td>
<td>0.147916</td>
</tr>
<tr>
<td>6</td>
<td>21.1</td>
<td>25.1</td>
<td>4.0</td>
<td>0.5670</td>
<td>33.96584</td>
<td>24.22050</td>
<td>0.641776</td>
<td>0.057260</td>
</tr>
<tr>
<td>7</td>
<td>21.0</td>
<td>25.6</td>
<td>4.6</td>
<td>0.5623</td>
<td>43.02445</td>
<td>27.85358</td>
<td>0.591095</td>
<td>0.071412</td>
</tr>
<tr>
<td>8</td>
<td>20.9</td>
<td>26.2</td>
<td>5.3</td>
<td>0.5649</td>
<td>55.13083</td>
<td>32.09216</td>
<td>0.538176</td>
<td>0.096275</td>
</tr>
<tr>
<td>9</td>
<td>20.8</td>
<td>26.6</td>
<td>5.8</td>
<td>0.5257</td>
<td>52.63220</td>
<td>35.11973</td>
<td>0.621248</td>
<td>0.138885</td>
</tr>
<tr>
<td>10</td>
<td>20.7</td>
<td>27.1</td>
<td>6.4</td>
<td>0.5130</td>
<td>58.19581</td>
<td>38.75280</td>
<td>0.624285</td>
<td>0.121698</td>
</tr>
</tbody>
</table>

Table D.10: Reproduction data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>$EPP^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.8</td>
<td>22.2</td>
<td>0.4</td>
<td>0</td>
<td>2.422050</td>
<td>–</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21.7</td>
<td>22.8</td>
<td>1.1</td>
<td>0.5737</td>
<td>7.969104</td>
<td>6.660638</td>
<td>0.531878</td>
<td>0.073459</td>
</tr>
<tr>
<td>2</td>
<td>21.7</td>
<td>23.4</td>
<td>1.7</td>
<td>0.5764</td>
<td>12.78728</td>
<td>10.29371</td>
<td>0.615585</td>
<td>0.075036</td>
</tr>
<tr>
<td>3</td>
<td>21.6</td>
<td>24.0</td>
<td>2.4</td>
<td>0.5832</td>
<td>19.85677</td>
<td>14.53230</td>
<td>0.609880</td>
<td>0.032271</td>
</tr>
<tr>
<td>4</td>
<td>21.6</td>
<td>24.6</td>
<td>3.0</td>
<td>0.5743</td>
<td>25.28053</td>
<td>18.16538</td>
<td>0.622745</td>
<td>0.030624</td>
</tr>
<tr>
<td>5</td>
<td>21.5</td>
<td>25.1</td>
<td>3.6</td>
<td>0.5800</td>
<td>31.56492</td>
<td>21.79845</td>
<td>0.613859</td>
<td>0.026690</td>
</tr>
<tr>
<td>6</td>
<td>21.4</td>
<td>25.5</td>
<td>4.1</td>
<td>0.5808</td>
<td>38.91781</td>
<td>24.82601</td>
<td>0.575674</td>
<td>0.088570</td>
</tr>
<tr>
<td>7</td>
<td>21.6</td>
<td>26.1</td>
<td>4.5</td>
<td>0.5363</td>
<td>41.40148</td>
<td>27.24806</td>
<td>0.599641</td>
<td>0.126510</td>
</tr>
<tr>
<td>8</td>
<td>21.6</td>
<td>26.7</td>
<td>5.1</td>
<td>0.5466</td>
<td>44.77657</td>
<td>30.88114</td>
<td>0.635580</td>
<td>0.081915</td>
</tr>
<tr>
<td>9</td>
<td>21.6</td>
<td>27.4</td>
<td>5.8</td>
<td>0.5400</td>
<td>51.26614</td>
<td>35.11973</td>
<td>0.637803</td>
<td>0.046422</td>
</tr>
<tr>
<td>10</td>
<td>21.6</td>
<td>27.8</td>
<td>6.2</td>
<td>0.5312</td>
<td>69.41492</td>
<td>37.54178</td>
<td>0.505939</td>
<td>0.095325</td>
</tr>
</tbody>
</table>

$^1$EPP: Energy Per Pulse
D.1.2 Configuration 2

Table D.11: Configuration 2 component values

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C_L</td>
<td>2.2 ( \mu )F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_th</td>
<td>2 nF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_tr</td>
<td>1.3 nF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L_s</td>
<td>1.5 mH</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

flow = 2.75 \( \ell/s \), Re \( \approx 8000 \)

Table D.12: First data

<table>
<thead>
<tr>
<th>#</th>
<th>( T_{in} ) (^{\circ} \text{C} )</th>
<th>( T_{out} ) (^{\circ} \text{C} )</th>
<th>( \Delta T ) (^{\circ} \text{C} )</th>
<th>EPP(^1) ([\text{J/pulse}])</th>
<th>Power ([\text{W}])</th>
<th>Q ([\text{W}])</th>
<th>( \eta )</th>
<th>std EPP(^1) ([\text{J/pulse}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>19.1</td>
<td>20.2</td>
<td>1.1</td>
<td>0</td>
<td>0</td>
<td>3.663351</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>19.2</td>
<td>21.7</td>
<td>2.5</td>
<td>0.6732</td>
<td>9.381434</td>
<td>8.325797</td>
<td>0.496986</td>
<td>0.042627</td>
</tr>
<tr>
<td>2</td>
<td>19.4</td>
<td>22.9</td>
<td>3.5</td>
<td>0.6611</td>
<td>16.73888</td>
<td>11.65612</td>
<td>0.477497</td>
<td>0.049137</td>
</tr>
<tr>
<td>3</td>
<td>19.5</td>
<td>24.0</td>
<td>4.5</td>
<td>0.6614</td>
<td>22.59957</td>
<td>14.98643</td>
<td>0.501031</td>
<td>0.039678</td>
</tr>
<tr>
<td>4</td>
<td>19.6</td>
<td>25.6</td>
<td>6.0</td>
<td>0.6737</td>
<td>31.45836</td>
<td>19.98191</td>
<td>0.518735</td>
<td>0.049885</td>
</tr>
<tr>
<td>5</td>
<td>19.6</td>
<td>26.7</td>
<td>7.1</td>
<td>0.6521</td>
<td>26.78652</td>
<td>23.64526</td>
<td>0.745969</td>
<td>0.045593</td>
</tr>
<tr>
<td>6</td>
<td>19.6</td>
<td>27.8</td>
<td>8.2</td>
<td>0.6245</td>
<td>46.80784</td>
<td>27.30861</td>
<td>0.505156</td>
<td>0.064268</td>
</tr>
<tr>
<td>7</td>
<td>19.7</td>
<td>29.1</td>
<td>9.4</td>
<td>0.6209</td>
<td>55.70398</td>
<td>31.30500</td>
<td>0.496224</td>
<td>0.074885</td>
</tr>
<tr>
<td>8</td>
<td>19.7</td>
<td>30.9</td>
<td>11.2</td>
<td>0.6344</td>
<td>54.32207</td>
<td>37.29957</td>
<td>0.619200</td>
<td>0.081406</td>
</tr>
<tr>
<td>9</td>
<td>19.7</td>
<td>31.8</td>
<td>12.1</td>
<td>0.6320</td>
<td>44.20465</td>
<td>40.29686</td>
<td>0.828725</td>
<td>0.097053</td>
</tr>
<tr>
<td>10</td>
<td>19.7</td>
<td>32.9</td>
<td>13.2</td>
<td>0.6074</td>
<td>43.51042</td>
<td>43.96021</td>
<td>0.926143</td>
<td>0.089659</td>
</tr>
</tbody>
</table>

\(^1\)EPP: Energy Per Pulse
### Table D.13: Reproduction data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17.2</td>
<td>17.9</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>2.331223</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>17.2</td>
<td>19.3</td>
<td>2.1</td>
<td>0.6355</td>
<td>7.954581</td>
<td>6.993669</td>
<td>0.586133</td>
<td>0.127045</td>
</tr>
<tr>
<td>2</td>
<td>17.4</td>
<td>20.3</td>
<td>2.9</td>
<td>0.6286</td>
<td>15.56185</td>
<td>9.657924</td>
<td>0.470812</td>
<td>0.061828</td>
</tr>
<tr>
<td>3</td>
<td>17.6</td>
<td>21.2</td>
<td>3.6</td>
<td>0.6586</td>
<td>24.91755</td>
<td>11.98915</td>
<td>0.387595</td>
<td>0.051210</td>
</tr>
<tr>
<td>4</td>
<td>17.9</td>
<td>22.4</td>
<td>4.5</td>
<td>0.6530</td>
<td>26.89617</td>
<td>14.98643</td>
<td>0.470521</td>
<td>0.065975</td>
</tr>
<tr>
<td>5</td>
<td>18.1</td>
<td>23.5</td>
<td>5.4</td>
<td>0.6040</td>
<td>38.12647</td>
<td>17.98372</td>
<td>0.410542</td>
<td>0.119064</td>
</tr>
<tr>
<td>6</td>
<td>18.2</td>
<td>24.5</td>
<td>6.3</td>
<td>0.6189</td>
<td>44.03185</td>
<td>20.98101</td>
<td>0.423552</td>
<td>0.140639</td>
</tr>
<tr>
<td>7</td>
<td>18.5</td>
<td>25.6</td>
<td>7.1</td>
<td>0.6078</td>
<td>39.58482</td>
<td>23.64526</td>
<td>0.538440</td>
<td>0.126455</td>
</tr>
<tr>
<td>8</td>
<td>18.5</td>
<td>26.5</td>
<td>8.0</td>
<td>0.6059</td>
<td>58.11763</td>
<td>26.64255</td>
<td>0.418312</td>
<td>0.060548</td>
</tr>
<tr>
<td>9</td>
<td>18.7</td>
<td>27.3</td>
<td>8.6</td>
<td>0.5822</td>
<td>61.21231</td>
<td>28.64074</td>
<td>0.429808</td>
<td>0.102789</td>
</tr>
<tr>
<td>10</td>
<td>18.6</td>
<td>28.1</td>
<td>9.5</td>
<td>0.5919</td>
<td>76.96970</td>
<td>31.63803</td>
<td>0.380758</td>
<td>0.054379</td>
</tr>
</tbody>
</table>
flow = 3.5 \ell/s, Re \approx 10000

Table D.14: First data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>19.6</td>
<td>20.7</td>
<td>1.1</td>
<td>0</td>
<td>0</td>
<td>4.662446</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>19.6</td>
<td>21.9</td>
<td>2.3</td>
<td>0.6640</td>
<td>10.25560</td>
<td>9.748751</td>
<td>0.495954</td>
<td>0.071198</td>
</tr>
<tr>
<td>2</td>
<td>19.8</td>
<td>22.9</td>
<td>3.1</td>
<td>0.6650</td>
<td>16.13158</td>
<td>13.13962</td>
<td>0.525502</td>
<td>0.059885</td>
</tr>
<tr>
<td>3</td>
<td>20.0</td>
<td>24.0</td>
<td>4.0</td>
<td>0.6735</td>
<td>21.27549</td>
<td>16.95435</td>
<td>0.577749</td>
<td>0.046534</td>
</tr>
<tr>
<td>4</td>
<td>20.2</td>
<td>25.1</td>
<td>4.9</td>
<td>0.6759</td>
<td>30.85409</td>
<td>20.76908</td>
<td>0.522026</td>
<td>0.066207</td>
</tr>
<tr>
<td>5</td>
<td>20.2</td>
<td>26.3</td>
<td>6.1</td>
<td>0.6834</td>
<td>41.34386</td>
<td>25.85538</td>
<td>0.512602</td>
<td>0.071043</td>
</tr>
<tr>
<td>6</td>
<td>20.2</td>
<td>27.3</td>
<td>7.1</td>
<td>0.6757</td>
<td>42.68764</td>
<td>30.09397</td>
<td>0.597588</td>
<td>0.084764</td>
</tr>
<tr>
<td>7</td>
<td>20.3</td>
<td>28.3</td>
<td>8.0</td>
<td>0.6711</td>
<td>61.37917</td>
<td>33.90870</td>
<td>0.476485</td>
<td>0.083859</td>
</tr>
<tr>
<td>8</td>
<td>20.3</td>
<td>29.7</td>
<td>9.4</td>
<td>0.6579</td>
<td>65.58822</td>
<td>39.84272</td>
<td>0.536381</td>
<td>0.090773</td>
</tr>
<tr>
<td>9</td>
<td>20.3</td>
<td>30.6</td>
<td>10.3</td>
<td>0.6617</td>
<td>45.80935</td>
<td>43.65475</td>
<td>0.851246</td>
<td>0.119985</td>
</tr>
<tr>
<td>10</td>
<td>20.5</td>
<td>31.2</td>
<td>10.7</td>
<td>0.6109</td>
<td>79.12690</td>
<td>45.35289</td>
<td>0.514243</td>
<td>0.130876</td>
</tr>
</tbody>
</table>

Table D.15: Reproduction data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.3</td>
<td>20.9</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
<td>2.543152</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20.2</td>
<td>21.9</td>
<td>1.7</td>
<td>0.6293</td>
<td>8.356243</td>
<td>7.205599</td>
<td>0.557960</td>
<td>0.061270</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>22.7</td>
<td>2.7</td>
<td>0.6333</td>
<td>13.39739</td>
<td>11.44419</td>
<td>0.664386</td>
<td>0.108895</td>
</tr>
<tr>
<td>3</td>
<td>20.1</td>
<td>23.4</td>
<td>3.3</td>
<td>0.6035</td>
<td>22.77017</td>
<td>13.98734</td>
<td>0.502596</td>
<td>0.134187</td>
</tr>
<tr>
<td>4</td>
<td>20.1</td>
<td>24.3</td>
<td>4.2</td>
<td>0.6572</td>
<td>32.96372</td>
<td>17.80207</td>
<td>0.462900</td>
<td>0.052195</td>
</tr>
<tr>
<td>5</td>
<td>20.1</td>
<td>25.0</td>
<td>4.9</td>
<td>0.6442</td>
<td>38.79790</td>
<td>20.76908</td>
<td>0.469766</td>
<td>0.119922</td>
</tr>
<tr>
<td>6</td>
<td>20.1</td>
<td>25.8</td>
<td>5.7</td>
<td>0.6311</td>
<td>45.15820</td>
<td>24.15995</td>
<td>0.462900</td>
<td>0.052195</td>
</tr>
<tr>
<td>7</td>
<td>20.0</td>
<td>26.7</td>
<td>6.7</td>
<td>0.6175</td>
<td>49.12825</td>
<td>28.39854</td>
<td>0.526283</td>
<td>0.077040</td>
</tr>
<tr>
<td>8</td>
<td>20.2</td>
<td>27.5</td>
<td>7.3</td>
<td>0.6360</td>
<td>52.39553</td>
<td>30.94169</td>
<td>0.542003</td>
<td>0.061330</td>
</tr>
<tr>
<td>9</td>
<td>20.2</td>
<td>28.0</td>
<td>7.8</td>
<td>0.6036</td>
<td>59.11480</td>
<td>33.06098</td>
<td>0.516247</td>
<td>0.077798</td>
</tr>
<tr>
<td>10</td>
<td>20.1</td>
<td>28.7</td>
<td>8.6</td>
<td>0.5893</td>
<td>70.37719</td>
<td>36.45185</td>
<td>0.481814</td>
<td>0.061086</td>
</tr>
</tbody>
</table>

$^I$EPP: Energy Per Pulse
flow = 4.4 ℓ/s, Re ≈ 13000

Table D.16: First data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18.8</td>
<td>20.0</td>
<td>1.2</td>
<td>0</td>
<td>0</td>
<td>6.394212</td>
<td>−</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>19.5</td>
<td>21.4</td>
<td>1.9</td>
<td>0.6426</td>
<td>8.889501</td>
<td>10.12417</td>
<td>0.419591</td>
<td>0.057790</td>
</tr>
<tr>
<td>2</td>
<td>19.6</td>
<td>22.3</td>
<td>2.7</td>
<td>0.6736</td>
<td>12.62854</td>
<td>14.38698</td>
<td>0.632913</td>
<td>0.054286</td>
</tr>
<tr>
<td>3</td>
<td>19.7</td>
<td>23.2</td>
<td>3.5</td>
<td>0.6682</td>
<td>22.97300</td>
<td>18.64979</td>
<td>0.533477</td>
<td>0.044395</td>
</tr>
<tr>
<td>4</td>
<td>19.7</td>
<td>24.1</td>
<td>4.4</td>
<td>0.6474</td>
<td>31.02749</td>
<td>23.44544</td>
<td>0.549552</td>
<td>0.520807</td>
</tr>
<tr>
<td>5</td>
<td>19.7</td>
<td>25.1</td>
<td>5.4</td>
<td>0.6648</td>
<td>36.38463</td>
<td>28.77395</td>
<td>0.615088</td>
<td>0.025173</td>
</tr>
<tr>
<td>6</td>
<td>20.1</td>
<td>26.0</td>
<td>5.9</td>
<td>0.6375</td>
<td>43.20839</td>
<td>31.43821</td>
<td>0.579610</td>
<td>0.063480</td>
</tr>
<tr>
<td>7</td>
<td>20.3</td>
<td>27.1</td>
<td>6.8</td>
<td>0.6606</td>
<td>40.76960</td>
<td>36.23387</td>
<td>0.731909</td>
<td>0.053291</td>
</tr>
<tr>
<td>8</td>
<td>20.4</td>
<td>28.3</td>
<td>7.9</td>
<td>0.6611</td>
<td>58.32397</td>
<td>42.09523</td>
<td>0.612116</td>
<td>0.072031</td>
</tr>
<tr>
<td>9</td>
<td>20.3</td>
<td>29.2</td>
<td>8.9</td>
<td>0.6373</td>
<td>66.15630</td>
<td>47.42374</td>
<td>0.620191</td>
<td>0.084833</td>
</tr>
<tr>
<td>10</td>
<td>20.8</td>
<td>29.9</td>
<td>9.1</td>
<td>0.5919</td>
<td>46.85567</td>
<td>48.48944</td>
<td>0.898402</td>
<td>0.102253</td>
</tr>
</tbody>
</table>

Table D.17: Reproduction data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.2</td>
<td>20.7</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>2.664255</td>
<td>−</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20.2</td>
<td>21.6</td>
<td>1.4</td>
<td>0.6581</td>
<td>8.887392</td>
<td>7.459914</td>
<td>0.539602</td>
<td>0.053068</td>
</tr>
<tr>
<td>2</td>
<td>20.2</td>
<td>22.4</td>
<td>2.2</td>
<td>0.6467</td>
<td>16.48848</td>
<td>11.72272</td>
<td>0.549382</td>
<td>0.045974</td>
</tr>
<tr>
<td>3</td>
<td>20.1</td>
<td>23.1</td>
<td>3.0</td>
<td>0.6513</td>
<td>24.90283</td>
<td>15.98553</td>
<td>0.534930</td>
<td>0.060250</td>
</tr>
<tr>
<td>4</td>
<td>20.1</td>
<td>23.9</td>
<td>3.8</td>
<td>0.6385</td>
<td>30.49485</td>
<td>20.24834</td>
<td>0.576625</td>
<td>0.115562</td>
</tr>
<tr>
<td>5</td>
<td>20.1</td>
<td>24.6</td>
<td>4.5</td>
<td>0.6517</td>
<td>38.34174</td>
<td>23.97830</td>
<td>0.555896</td>
<td>0.057601</td>
</tr>
<tr>
<td>6</td>
<td>20.1</td>
<td>25.2</td>
<td>5.1</td>
<td>0.6319</td>
<td>49.06694</td>
<td>27.17540</td>
<td>0.499545</td>
<td>0.070964</td>
</tr>
<tr>
<td>7</td>
<td>20.0</td>
<td>26.1</td>
<td>6.1</td>
<td>0.6559</td>
<td>53.32221</td>
<td>32.50391</td>
<td>0.559610</td>
<td>0.059550</td>
</tr>
<tr>
<td>8</td>
<td>20.3</td>
<td>26.5</td>
<td>6.2</td>
<td>0.6165</td>
<td>50.54593</td>
<td>33.03676</td>
<td>0.600889</td>
<td>0.089260</td>
</tr>
<tr>
<td>9</td>
<td>20.3</td>
<td>27.3</td>
<td>7.0</td>
<td>0.5996</td>
<td>66.14379</td>
<td>37.29957</td>
<td>0.523637</td>
<td>0.116336</td>
</tr>
<tr>
<td>10</td>
<td>20.3</td>
<td>28.0</td>
<td>7.7</td>
<td>0.6015</td>
<td>64.85685</td>
<td>41.02953</td>
<td>0.591538</td>
<td>0.096748</td>
</tr>
</tbody>
</table>

$^1$EPP: Energy Per Pulse
flow = 5.0 \, \frac{\text{g}}{\text{s}}, \, \text{Re} \approx 15000

<table>
<thead>
<tr>
<th></th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>EPP$^I$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^I$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.8</td>
<td>22.3</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>3.027563</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>21.8</td>
<td>23.1</td>
<td>1.3</td>
<td>0.5942</td>
<td>6.989736</td>
<td>7.871663</td>
<td>0.693031</td>
<td>0.147223</td>
</tr>
<tr>
<td>2</td>
<td>21.8</td>
<td>23.7</td>
<td>1.9</td>
<td>0.5566</td>
<td>12.68794</td>
<td>11.50474</td>
<td>0.668128</td>
<td>0.188014</td>
</tr>
<tr>
<td>3</td>
<td>21.8</td>
<td>24.2</td>
<td>2.4</td>
<td>0.5777</td>
<td>24.53684</td>
<td>14.53230</td>
<td>0.468876</td>
<td>0.201496</td>
</tr>
<tr>
<td>4</td>
<td>21.7</td>
<td>24.9</td>
<td>3.2</td>
<td>0.6462</td>
<td>30.02477</td>
<td>19.37640</td>
<td>0.544512</td>
<td>0.073497</td>
</tr>
<tr>
<td>5</td>
<td>21.7</td>
<td>25.6</td>
<td>3.9</td>
<td>0.6491</td>
<td>35.90991</td>
<td>23.61499</td>
<td>0.573308</td>
<td>0.073626</td>
</tr>
<tr>
<td>6</td>
<td>21.8</td>
<td>26.3</td>
<td>4.5</td>
<td>0.6633</td>
<td>43.60341</td>
<td>27.24806</td>
<td>0.555473</td>
<td>0.053459</td>
</tr>
<tr>
<td>7</td>
<td>21.9</td>
<td>27.2</td>
<td>5.3</td>
<td>0.6530</td>
<td>54.73512</td>
<td>32.09216</td>
<td>0.531005</td>
<td>0.064918</td>
</tr>
<tr>
<td>8</td>
<td>21.9</td>
<td>27.9</td>
<td>6.0</td>
<td>0.6387</td>
<td>58.13116</td>
<td>36.33075</td>
<td>0.572897</td>
<td>0.071933</td>
</tr>
<tr>
<td>9</td>
<td>21.9</td>
<td>28.5</td>
<td>6.6</td>
<td>0.6143</td>
<td>62.30115</td>
<td>39.96383</td>
<td>0.592866</td>
<td>0.096051</td>
</tr>
<tr>
<td>10</td>
<td>21.9</td>
<td>29.2</td>
<td>7.3</td>
<td>0.5957</td>
<td>74.09664</td>
<td>44.20241</td>
<td>0.555691</td>
<td>0.130017</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>EPP$^I$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^I$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.1</td>
<td>20.6</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>3.027563</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>20.3</td>
<td>21.7</td>
<td>1.4</td>
<td>0.6073</td>
<td>8.204412</td>
<td>8.477175</td>
<td>0.664229</td>
<td>0.134118</td>
</tr>
<tr>
<td>2</td>
<td>20.5</td>
<td>22.4</td>
<td>1.9</td>
<td>0.6151</td>
<td>13.08766</td>
<td>11.50474</td>
<td>0.647723</td>
<td>0.150805</td>
</tr>
<tr>
<td>3</td>
<td>20.6</td>
<td>23.3</td>
<td>2.7</td>
<td>0.6406</td>
<td>21.67563</td>
<td>16.34884</td>
<td>0.614574</td>
<td>0.080949</td>
</tr>
<tr>
<td>4</td>
<td>20.8</td>
<td>24.3</td>
<td>3.5</td>
<td>0.6624</td>
<td>35.50675</td>
<td>21.19294</td>
<td>0.511603</td>
<td>0.083537</td>
</tr>
<tr>
<td>5</td>
<td>20.9</td>
<td>25.1</td>
<td>4.2</td>
<td>0.6641</td>
<td>40.80008</td>
<td>25.43153</td>
<td>0.549116</td>
<td>0.039394</td>
</tr>
<tr>
<td>6</td>
<td>20.9</td>
<td>25.9</td>
<td>5.0</td>
<td>0.6631</td>
<td>45.22529</td>
<td>30.27563</td>
<td>0.602496</td>
<td>0.050894</td>
</tr>
<tr>
<td>7</td>
<td>21.0</td>
<td>26.4</td>
<td>5.4</td>
<td>0.6691</td>
<td>47.86990</td>
<td>32.69768</td>
<td>0.619807</td>
<td>0.045285</td>
</tr>
<tr>
<td>8</td>
<td>21.1</td>
<td>27.0</td>
<td>5.9</td>
<td>0.6280</td>
<td>58.61112</td>
<td>35.72524</td>
<td>0.557875</td>
<td>0.100392</td>
</tr>
<tr>
<td>9</td>
<td>21.1</td>
<td>27.7</td>
<td>6.6</td>
<td>0.6054</td>
<td>59.21870</td>
<td>39.96383</td>
<td>0.623726</td>
<td>0.040565</td>
</tr>
<tr>
<td>10</td>
<td>21.2</td>
<td>28.5</td>
<td>7.3</td>
<td>0.6305</td>
<td>71.39195</td>
<td>44.20241</td>
<td>0.576744</td>
<td>0.042436</td>
</tr>
</tbody>
</table>

$^I$EPP: Energy Per Pulse
D.1.3 Configuration 3

Table D.20: Configuration 3 component values

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_L$</td>
<td>2.2 $\mu$F</td>
<td></td>
</tr>
<tr>
<td>$C_{th}$</td>
<td>2 nF</td>
<td></td>
</tr>
<tr>
<td>$C_{tr}$</td>
<td>1.3 nF</td>
<td></td>
</tr>
<tr>
<td>$L_5$</td>
<td>4.5 mH</td>
<td></td>
</tr>
</tbody>
</table>

flow = 2.75 l/s, Re $\approx$ 8000

Table D.21: First data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17.8</td>
<td>18.2</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>1.332128</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>17.6</td>
<td>19.5</td>
<td>1.9</td>
<td>0.6361</td>
<td>8.712483</td>
<td>6.327606</td>
<td>0.573370</td>
<td>0.019525</td>
</tr>
<tr>
<td>2</td>
<td>17.4</td>
<td>20.7</td>
<td>3.3</td>
<td>0.6345</td>
<td>15.95578</td>
<td>10.99005</td>
<td>0.605293</td>
<td>0.020678</td>
</tr>
<tr>
<td>3</td>
<td>17.2</td>
<td>21.9</td>
<td>4.7</td>
<td>0.6482</td>
<td>22.54080</td>
<td>15.65250</td>
<td>0.635309</td>
<td>0.016278</td>
</tr>
<tr>
<td>4</td>
<td>17.1</td>
<td>23.3</td>
<td>6.2</td>
<td>0.6740</td>
<td>31.38579</td>
<td>20.64798</td>
<td>0.615433</td>
<td>0.018611</td>
</tr>
<tr>
<td>5</td>
<td>17.1</td>
<td>24.8</td>
<td>7.7</td>
<td>0.6830</td>
<td>36.23601</td>
<td>25.64345</td>
<td>0.670916</td>
<td>0.024314</td>
</tr>
<tr>
<td>6</td>
<td>17.0</td>
<td>26.3</td>
<td>9.3</td>
<td>0.7011</td>
<td>44.02459</td>
<td>30.97196</td>
<td>0.673256</td>
<td>0.026161</td>
</tr>
<tr>
<td>7</td>
<td>17.0</td>
<td>27.8</td>
<td>10.8</td>
<td>0.6862</td>
<td>46.23589</td>
<td>35.96744</td>
<td>0.749100</td>
<td>0.033812</td>
</tr>
<tr>
<td>8</td>
<td>17.0</td>
<td>29.2</td>
<td>12.2</td>
<td>0.6804</td>
<td>58.93060</td>
<td>40.62989</td>
<td>0.666848</td>
<td>0.052363</td>
</tr>
<tr>
<td>9</td>
<td>17.0</td>
<td>30.3</td>
<td>13.3</td>
<td>0.6609</td>
<td>72.56759</td>
<td>44.29324</td>
<td>0.592015</td>
<td>0.074824</td>
</tr>
<tr>
<td>10</td>
<td>16.9</td>
<td>31.6</td>
<td>14.7</td>
<td>0.6588</td>
<td>75.15767</td>
<td>48.95569</td>
<td>0.633649</td>
<td>0.069742</td>
</tr>
</tbody>
</table>

$^1$ EPP: Energy Per Pulse
Table D.22: Reproduction data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>EPP$^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.5</td>
<td>17.0</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>1.665159</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>16.3</td>
<td>18.1</td>
<td>1.8</td>
<td>0.5915</td>
<td>7.690362</td>
<td>5.994574</td>
<td>0.562966</td>
<td>0.019055</td>
</tr>
<tr>
<td>2</td>
<td>16.2</td>
<td>18.9</td>
<td>2.7</td>
<td>0.6063</td>
<td>14.58534</td>
<td>8.991861</td>
<td>0.502333</td>
<td>0.029982</td>
</tr>
<tr>
<td>3</td>
<td>16.2</td>
<td>19.8</td>
<td>3.6</td>
<td>0.6183</td>
<td>21.22358</td>
<td>11.98915</td>
<td>0.486440</td>
<td>0.018323</td>
</tr>
<tr>
<td>4</td>
<td>16.1</td>
<td>20.8</td>
<td>4.7</td>
<td>0.6361</td>
<td>28.29241</td>
<td>15.65250</td>
<td>0.494385</td>
<td>0.024605</td>
</tr>
<tr>
<td>5</td>
<td>16.1</td>
<td>22.1</td>
<td>6.0</td>
<td>0.6454</td>
<td>36.95123</td>
<td>19.98191</td>
<td>0.495701</td>
<td>0.024761</td>
</tr>
<tr>
<td>6</td>
<td>15.9</td>
<td>22.9</td>
<td>7.0</td>
<td>0.6686</td>
<td>46.85862</td>
<td>23.31223</td>
<td>0.461966</td>
<td>0.027733</td>
</tr>
<tr>
<td>7</td>
<td>15.9</td>
<td>24.1</td>
<td>8.2</td>
<td>0.6585</td>
<td>53.47530</td>
<td>27.30861</td>
<td>0.479538</td>
<td>0.034323</td>
</tr>
<tr>
<td>8</td>
<td>15.8</td>
<td>24.9</td>
<td>9.1</td>
<td>0.6407</td>
<td>53.70621</td>
<td>30.30590</td>
<td>0.533285</td>
<td>0.040429</td>
</tr>
<tr>
<td>9</td>
<td>15.9</td>
<td>26.0</td>
<td>10.1</td>
<td>0.6358</td>
<td>67.0524</td>
<td>33.63622</td>
<td>0.476807</td>
<td>0.052299</td>
</tr>
<tr>
<td>10</td>
<td>15.9</td>
<td>26.9</td>
<td>11.0</td>
<td>0.6170</td>
<td>67.72642</td>
<td>36.63351</td>
<td>0.516318</td>
<td>0.061265</td>
</tr>
</tbody>
</table>
flow = 3.5 $\ell$/s, Re $\approx 10000$

### Table D.23: First data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ $[^{\circ}\text{C}]$</th>
<th>$T_{out}$ $[^{\circ}\text{C}]$</th>
<th>$\Delta T$ $[^{\circ}\text{C}]$</th>
<th>EPP$^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$Q$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.3</td>
<td>16.0</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>2.967011</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1</td>
<td>15.1</td>
<td>17.0</td>
<td>1.9</td>
<td>0.6520</td>
<td>8.177022</td>
<td>8.053316</td>
<td>0.622024</td>
<td>0.03346</td>
</tr>
<tr>
<td>2</td>
<td>15.3</td>
<td>17.9</td>
<td>2.6</td>
<td>0.6470</td>
<td>16.29788</td>
<td>11.02033</td>
<td>0.494133</td>
<td>0.031192</td>
</tr>
<tr>
<td>3</td>
<td>15.5</td>
<td>19.0</td>
<td>3.5</td>
<td>0.6380</td>
<td>21.25911</td>
<td>14.83506</td>
<td>0.558257</td>
<td>0.030792</td>
</tr>
<tr>
<td>4</td>
<td>15.7</td>
<td>19.9</td>
<td>4.2</td>
<td>0.6556</td>
<td>30.12872</td>
<td>17.80207</td>
<td>0.492389</td>
<td>0.027264</td>
</tr>
<tr>
<td>5</td>
<td>15.9</td>
<td>21.0</td>
<td>5.1</td>
<td>0.6550</td>
<td>34.47025</td>
<td>21.61680</td>
<td>0.541040</td>
<td>0.027671</td>
</tr>
<tr>
<td>6</td>
<td>16.0</td>
<td>22.1</td>
<td>6.1</td>
<td>0.6530</td>
<td>44.49010</td>
<td>25.85538</td>
<td>0.514460</td>
<td>0.028311</td>
</tr>
<tr>
<td>7</td>
<td>16.2</td>
<td>23.1</td>
<td>6.9</td>
<td>0.6750</td>
<td>51.25202</td>
<td>29.24625</td>
<td>0.512745</td>
<td>0.021526</td>
</tr>
<tr>
<td>8</td>
<td>16.4</td>
<td>23.8</td>
<td>7.4</td>
<td>0.6388</td>
<td>54.40385</td>
<td>31.36555</td>
<td>0.521995</td>
<td>0.039894</td>
</tr>
<tr>
<td>9</td>
<td>16.5</td>
<td>24.6</td>
<td>8.1</td>
<td>0.6383</td>
<td>66.36272</td>
<td>34.33256</td>
<td>0.472638</td>
<td>0.043338</td>
</tr>
<tr>
<td>10</td>
<td>16.9</td>
<td>25.8</td>
<td>8.9</td>
<td>0.6097</td>
<td>66.12412</td>
<td>37.72343</td>
<td>0.525624</td>
<td>0.046921</td>
</tr>
</tbody>
</table>

### Table D.24: Reproduction data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ $[^{\circ}\text{C}]$</th>
<th>$T_{out}$ $[^{\circ}\text{C}]$</th>
<th>$\Delta T$ $[^{\circ}\text{C}]$</th>
<th>EPP$^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$Q$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.7</td>
<td>16.1</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>1.695435</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1</td>
<td>15.8</td>
<td>17.4</td>
<td>1.6</td>
<td>0.6445</td>
<td>8.602577</td>
<td>6.781740</td>
<td>0.591254</td>
<td>0.020921</td>
</tr>
<tr>
<td>2</td>
<td>15.8</td>
<td>18.4</td>
<td>2.6</td>
<td>0.5852</td>
<td>14.03773</td>
<td>11.02033</td>
<td>0.664274</td>
<td>0.023618</td>
</tr>
<tr>
<td>3</td>
<td>16.0</td>
<td>19.1</td>
<td>3.1</td>
<td>0.5998</td>
<td>20.77250</td>
<td>13.13962</td>
<td>0.550930</td>
<td>0.024275</td>
</tr>
<tr>
<td>4</td>
<td>16.0</td>
<td>20.2</td>
<td>4.2</td>
<td>0.6384</td>
<td>28.90492</td>
<td>17.80207</td>
<td>0.557228</td>
<td>0.018748</td>
</tr>
<tr>
<td>5</td>
<td>15.8</td>
<td>20.9</td>
<td>5.1</td>
<td>0.6969</td>
<td>38.96806</td>
<td>21.61680</td>
<td>0.511223</td>
<td>0.021755</td>
</tr>
<tr>
<td>6</td>
<td>16.1</td>
<td>21.8</td>
<td>5.7</td>
<td>0.7180</td>
<td>47.78923</td>
<td>24.15995</td>
<td>0.470075</td>
<td>0.028358</td>
</tr>
<tr>
<td>7</td>
<td>16.1</td>
<td>22.9</td>
<td>6.8</td>
<td>0.6471</td>
<td>49.95730</td>
<td>28.82240</td>
<td>0.543003</td>
<td>0.028627</td>
</tr>
<tr>
<td>8</td>
<td>16.4</td>
<td>23.7</td>
<td>7.3</td>
<td>0.6991</td>
<td>61.41108</td>
<td>30.94169</td>
<td>0.476237</td>
<td>0.029020</td>
</tr>
<tr>
<td>9</td>
<td>16.5</td>
<td>24.5</td>
<td>8.0</td>
<td>0.6386</td>
<td>62.89451</td>
<td>33.90870</td>
<td>0.512179</td>
<td>0.035361</td>
</tr>
<tr>
<td>10</td>
<td>16.4</td>
<td>25.4</td>
<td>9.0</td>
<td>0.6577</td>
<td>71.77237</td>
<td>38.14729</td>
<td>0.507881</td>
<td>0.045564</td>
</tr>
</tbody>
</table>

$^1$EPP: Energy Per Pulse
Appendix D  Measurement data

flow = 4.4 ℓ/s, Re ≈ 13000

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>EPP $^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP $^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17.3</td>
<td>17.8</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>2.664255</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>17.4</td>
<td>18.9</td>
<td>1.5</td>
<td>0.6480</td>
<td>8.417296</td>
<td>7.992765</td>
<td>0.633043</td>
<td>0.024516</td>
</tr>
<tr>
<td>2</td>
<td>17.9</td>
<td>20.0</td>
<td>2.1</td>
<td>0.6476</td>
<td>14.73957</td>
<td>11.18987</td>
<td>0.578417</td>
<td>0.026595</td>
</tr>
<tr>
<td>3</td>
<td>18.0</td>
<td>21.0</td>
<td>3.0</td>
<td>0.6555</td>
<td>23.46616</td>
<td>15.98553</td>
<td>0.567680</td>
<td>0.022141</td>
</tr>
<tr>
<td>4</td>
<td>17.9</td>
<td>22.0</td>
<td>4.1</td>
<td>0.6605</td>
<td>30.70587</td>
<td>21.84689</td>
<td>0.624722</td>
<td>0.018968</td>
</tr>
<tr>
<td>5</td>
<td>17.9</td>
<td>23.1</td>
<td>5.2</td>
<td>0.6674</td>
<td>38.05132</td>
<td>27.70825</td>
<td>0.658164</td>
<td>0.019967</td>
</tr>
<tr>
<td>6</td>
<td>18.0</td>
<td>24.2</td>
<td>6.2</td>
<td>0.6889</td>
<td>46.96684</td>
<td>33.03676</td>
<td>0.646680</td>
<td>0.022059</td>
</tr>
<tr>
<td>7</td>
<td>18.0</td>
<td>25.1</td>
<td>7.1</td>
<td>0.6838</td>
<td>56.64960</td>
<td>37.83242</td>
<td>0.620802</td>
<td>0.024268</td>
</tr>
<tr>
<td>8</td>
<td>18.0</td>
<td>26.2</td>
<td>8.2</td>
<td>0.6788</td>
<td>57.65646</td>
<td>43.69378</td>
<td>0.711621</td>
<td>0.038498</td>
</tr>
<tr>
<td>9</td>
<td>18.0</td>
<td>27.0</td>
<td>9.0</td>
<td>0.6682</td>
<td>69.18398</td>
<td>47.95659</td>
<td>0.654665</td>
<td>0.052474</td>
</tr>
<tr>
<td>10</td>
<td>17.8</td>
<td>27.5</td>
<td>9.7</td>
<td>0.5762</td>
<td>67.53654</td>
<td>51.68655</td>
<td>0.725863</td>
<td>0.075528</td>
</tr>
</tbody>
</table>

Table D.26: Reproduction data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$\Delta T$ [°C]</th>
<th>EPP $^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$\dot{Q}$ [W]</th>
<th>$\eta$</th>
<th>std EPP $^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.3</td>
<td>16.8</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>2.664255</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>16.2</td>
<td>17.7</td>
<td>1.5</td>
<td>0.6088</td>
<td>8.122523</td>
<td>7.992765</td>
<td>0.656017</td>
<td>0.023164</td>
</tr>
<tr>
<td>2</td>
<td>16.2</td>
<td>18.4</td>
<td>2.2</td>
<td>0.6090</td>
<td>14.08883</td>
<td>11.72272</td>
<td>0.642954</td>
<td>0.027730</td>
</tr>
<tr>
<td>3</td>
<td>16.6</td>
<td>19.2</td>
<td>2.6</td>
<td>0.6225</td>
<td>18.81452</td>
<td>13.85413</td>
<td>0.594746</td>
<td>0.027435</td>
</tr>
<tr>
<td>4</td>
<td>16.6</td>
<td>20.0</td>
<td>3.4</td>
<td>0.6359</td>
<td>28.35883</td>
<td>18.11693</td>
<td>0.544898</td>
<td>0.026560</td>
</tr>
<tr>
<td>5</td>
<td>16.7</td>
<td>20.9</td>
<td>4.2</td>
<td>0.6466</td>
<td>37.79791</td>
<td>22.37974</td>
<td>0.521603</td>
<td>0.025095</td>
</tr>
<tr>
<td>6</td>
<td>16.6</td>
<td>21.7</td>
<td>5.1</td>
<td>0.6609</td>
<td>41.54165</td>
<td>27.17540</td>
<td>0.590038</td>
<td>0.024493</td>
</tr>
<tr>
<td>7</td>
<td>17.0</td>
<td>22.4</td>
<td>5.4</td>
<td>0.6901</td>
<td>55.96615</td>
<td>28.77395</td>
<td>0.466527</td>
<td>0.027947</td>
</tr>
<tr>
<td>8</td>
<td>16.9</td>
<td>23.2</td>
<td>6.3</td>
<td>0.6595</td>
<td>61.48100</td>
<td>33.56961</td>
<td>0.502681</td>
<td>0.037553</td>
</tr>
<tr>
<td>9</td>
<td>16.9</td>
<td>23.9</td>
<td>7.0</td>
<td>0.6385</td>
<td>61.42405</td>
<td>37.29957</td>
<td>0.563872</td>
<td>0.033940</td>
</tr>
<tr>
<td>10</td>
<td>16.8</td>
<td>24.4</td>
<td>7.6</td>
<td>0.6172</td>
<td>66.54273</td>
<td>40.49668</td>
<td>0.568543</td>
<td>0.045416</td>
</tr>
</tbody>
</table>

$^1$EPP: Energy Per Pulse
flow = 5.0 l/s, Re \approx 15000

### Table D.27: First data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [$^\circ$C]</th>
<th>$T_{out}$ [$^\circ$C]</th>
<th>$\Delta T$</th>
<th>EPP$^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$Q$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.9</td>
<td>22.4</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>3.027563</td>
<td>–</td>
<td>0.0000</td>
</tr>
<tr>
<td>1</td>
<td>21.9</td>
<td>23.4</td>
<td>1.5</td>
<td>0.6534</td>
<td>9.003585</td>
<td>9.082688</td>
<td>0.672524</td>
<td>0.038774</td>
</tr>
<tr>
<td>2</td>
<td>21.9</td>
<td>24.2</td>
<td>2.3</td>
<td>0.6681</td>
<td>16.99478</td>
<td>13.92679</td>
<td>0.641328</td>
<td>0.023282</td>
</tr>
<tr>
<td>3</td>
<td>21.9</td>
<td>24.9</td>
<td>3.0</td>
<td>0.6609</td>
<td>23.38159</td>
<td>18.16538</td>
<td>0.647424</td>
<td>0.029138</td>
</tr>
<tr>
<td>4</td>
<td>21.9</td>
<td>25.6</td>
<td>3.7</td>
<td>0.6694</td>
<td>31.77614</td>
<td>22.40396</td>
<td>0.609778</td>
<td>0.023170</td>
</tr>
<tr>
<td>5</td>
<td>21.9</td>
<td>26.3</td>
<td>4.4</td>
<td>0.6594</td>
<td>36.31508</td>
<td>26.64255</td>
<td>0.650281</td>
<td>0.021980</td>
</tr>
<tr>
<td>6</td>
<td>21.9</td>
<td>27.1</td>
<td>5.2</td>
<td>0.6689</td>
<td>44.91600</td>
<td>31.48665</td>
<td>0.633607</td>
<td>0.025650</td>
</tr>
<tr>
<td>7</td>
<td>21.8</td>
<td>27.8</td>
<td>6.0</td>
<td>0.7015</td>
<td>53.07471</td>
<td>36.33075</td>
<td>0.627478</td>
<td>0.036755</td>
</tr>
<tr>
<td>8</td>
<td>21.9</td>
<td>28.6</td>
<td>6.7</td>
<td>0.6786</td>
<td>63.92731</td>
<td>40.56934</td>
<td>0.587257</td>
<td>0.056532</td>
</tr>
<tr>
<td>9</td>
<td>21.9</td>
<td>29.3</td>
<td>7.4</td>
<td>0.6688</td>
<td>74.47621</td>
<td>44.80793</td>
<td>0.560989</td>
<td>0.059841</td>
</tr>
<tr>
<td>10</td>
<td>21.9</td>
<td>30.2</td>
<td>8.3</td>
<td>0.6776</td>
<td>76.49620</td>
<td>50.25754</td>
<td>0.617416</td>
<td>0.064222</td>
</tr>
</tbody>
</table>

### Table D.28: Reproduction data

<table>
<thead>
<tr>
<th>#</th>
<th>$T_{in}$ [$^\circ$C]</th>
<th>$T_{out}$ [$^\circ$C]</th>
<th>$\Delta T$</th>
<th>EPP$^1$ [J/pulse]</th>
<th>Power [W]</th>
<th>$Q$ [W]</th>
<th>$\eta$</th>
<th>std EPP$^1$ [J/pulse]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.9</td>
<td>22.4</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>3.027563</td>
<td>–</td>
<td>0.0000</td>
</tr>
<tr>
<td>1</td>
<td>21.8</td>
<td>23.4</td>
<td>1.5</td>
<td>0.6768</td>
<td>8.890356</td>
<td>9.688200</td>
<td>0.749198</td>
<td>0.033516</td>
</tr>
<tr>
<td>2</td>
<td>21.8</td>
<td>24.0</td>
<td>2.2</td>
<td>0.6705</td>
<td>16.32487</td>
<td>13.32128</td>
<td>0.630554</td>
<td>0.025969</td>
</tr>
<tr>
<td>3</td>
<td>21.8</td>
<td>24.7</td>
<td>2.9</td>
<td>0.6807</td>
<td>21.81457</td>
<td>17.55986</td>
<td>0.666174</td>
<td>0.027144</td>
</tr>
<tr>
<td>4</td>
<td>21.8</td>
<td>25.5</td>
<td>3.7</td>
<td>0.6913</td>
<td>30.19065</td>
<td>22.40396</td>
<td>0.641801</td>
<td>0.031834</td>
</tr>
<tr>
<td>5</td>
<td>21.8</td>
<td>26.1</td>
<td>4.3</td>
<td>0.6861</td>
<td>39.59359</td>
<td>26.03704</td>
<td>0.581141</td>
<td>0.033218</td>
</tr>
<tr>
<td>6</td>
<td>21.8</td>
<td>27.1</td>
<td>5.3</td>
<td>0.6830</td>
<td>44.96971</td>
<td>32.09216</td>
<td>0.646315</td>
<td>0.022496</td>
</tr>
<tr>
<td>7</td>
<td>21.8</td>
<td>27.8</td>
<td>6.0</td>
<td>0.6964</td>
<td>52.04363</td>
<td>36.33075</td>
<td>0.639909</td>
<td>0.023286</td>
</tr>
<tr>
<td>8</td>
<td>21.8</td>
<td>28.5</td>
<td>6.7</td>
<td>0.6780</td>
<td>55.19522</td>
<td>40.56934</td>
<td>0.680164</td>
<td>0.046060</td>
</tr>
<tr>
<td>9</td>
<td>21.8</td>
<td>29.3</td>
<td>7.5</td>
<td>0.6798</td>
<td>66.26108</td>
<td>45.41344</td>
<td>0.639680</td>
<td>0.048112</td>
</tr>
<tr>
<td>10</td>
<td>21.8</td>
<td>29.8</td>
<td>8.0</td>
<td>0.6605</td>
<td>69.47178</td>
<td>48.44100</td>
<td>0.653696</td>
<td>0.049787</td>
</tr>
</tbody>
</table>

$^1$EPP: Energy Per Pulse
Appendix E

Abstract Symposium Pulsed Power and Plasma Applications

The following abstract was submitted to the 6th International Symposium on Pulsed Power and Plasma Applications, Chengdu, Sichuan, China, 18–22 September 2006.
Characteristics of a Novel Multiple Pulsed Plasma Torch


Department of Electrical Engineering, Eindhoven University of Technology, The Netherlands
Email: a.j.m.pemen@tue.nl; phone: +31 40 247 4494; fax: +31 40 245 0735

Abstract

Traditional thermal plasmas usually generate a very high temperature or high heat flux. The main characteristic of plasma torches operating under arc discharge mode is the extremely high temperature (several thousand degree centigrade) confined in a small volume. High temperatures during the discharge phenomena are very useful in some processes such as incineration treatments. But in other applications, such as chemical processes, the impossibility (or the limitation) to control thermal effects can lead to undesired by-products. Often, the use of a non-reactive gas such as argon or a cooling system can reduce some of the problems related to high temperature (electrode-life and the reactor thermal stresses) but, at the same time, reduces the heating efficiency.

Pulsed technology presents the advantages of a tunable power supply with control by a variable duty cycle of active plasma and plasma afterglow (energy efficiency). The immediate consequence of this is the major homogeneity of the plasma characteristics since pulsed energization in conjunction with rapid gas exchange among pulses can promote heat and mass transfer between plasma boundary and the plasma center. This latter is an important feature especially in presence of chemical reactions since transport phenomena can play a key role in selectivity pattern (output quality). Non-continuous discharges pulsed at high repetition rate are intrinsically stable and this together with the use of a new multiple switch concept for the realization of multiple plasma torches can give larger reactor volume for processing (reliability and size). Pulsed technology, thus, seems to solve the scale-up problems of the plasma sources since changing the linear dimension of conventional plasma sources, keeping the same proprieties, is not simple. Finally repetitive pulsed power appears also able to generate a new kind of plasma, the transient plasma (not thermal plasma, not cold plasma), which the thermo-physic properties depend on the electric and temporal features of the discharge stages.

This paper presents some issues on a novel atmospheric pressure pulsed plasma torch, as introduced by Keping Yan. A high-voltage pulse generator is used to induce transient plasma in a gas flow (air) under different conditions of pulse repetition rates, energizing levels and mass flow rates. A dedicated multi-torch reactor, with rod-to-rod electrode type, was built to perform studies on electrical behavior and thermal effects of the generated pulsed plasma. The pulsed plasma torch is achieved in plug-flow like reactor under turbulent conditions of the gas flow.