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Air flow and arc cooling in load break switch

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Problem description

In today's high voltage equipment, SF_6 is the main insulation and interruption medium. However, it is classified as a potent greenhouse gas with a very high global warming potential. Therefore, the industry has begun looking for other technologies. NTNU and SINTEF Energy Research are currently carrying out an extensive R&D program for ABB Skien on medium voltage load break switches with air as an interruption medium. To make air-filled switchgear as compact as today's SF_6, a better understanding of air as an interruption media needs to be obtained.

The main topic of the project work will be the study of the air flow during the cooling process of an arc. The work will consist of both laboratory experiments and heat distribution simulations in the finite element computation software, COMSOL Multiphysics. A simplified experimental laboratory setup is made, simulating an arc with an electrically heated wolfram wire. The setup is used for testing of various wire dimensions and placements for different air flow designs, where the cooling power is mapped as a reduction of the temperature along the wire.

Preface

This report is the result of my master's thesis work at Norwegian University of Science and Technology (NTNU) and is written during the spring semester 2017. The project has been performed in collaboration with SINTEF Energy Research. It is a continuation of my specialization project and aims at determining how the air flow should be designed to obtain the best interruption performance. The work has been conducted in laboratory experiments and further compared with finite element simulations performed using COMSOL Multiphysics.

Firstly, I would like to thank Professor Kaveh Niayesh at NTNU for giving me the opportunity to undertake this project and helping me on the way. I appreciate all the times you have left your office door open for me to come in with all my questions.

I am grateful to Ph.D Erik Jonsson, Research Scientist at SINEF Energy Research, as he has been my main source of guidance and support during develompent of the labratory experiments. He has also helped me further with my understanding on several issues.

I would also like to thank Hallvar Haugdal for guidance in COMSOL.

Finally, I would like to thank the workshop and service laboratory at NTNU for helping me providing the required equipment needed to carry out the experiments for this master thesis.

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Abstract

Current interruption is a complex process, and optimizing the design of a medium voltage load-break switch is difficult. The dominating technology for load-break switches in medium voltage switchgear is using SF_6 as interruption medium. SF_6 is classified as a potent greenhouse gas with very high global warming potential. Thus, the industry has begun looking at other technologies. One interesting option is to quench the arc using air. When using air instead of SF_6, optimization with regard to size is important since larger equipment will not fit in many existing installation sites. Due to the superior properties of SF_6, little research has been done with air as an interrupting medium in load-break switches.

The thesis addresses medium-voltage load current interruption in air. The project work has focused on determining how the air flow should be designed to obtain the best interruption performance in a load-break switch. A simplified experimental setup based on steady-state air flow and with an electrically heated wolfram wire, simulating the arc, was used. Two different air flow designs were made and tested in the laboratory: axial and radial flow. With the axial design, the air flow was blown straight on the wire. With the radial design, the air flow was blown 90° onto the wire. Two different wire diameters for the simulated arc were tested to simulate the arc, 0.15 and 0.38 mm. The radial design proved to be 35 % more efficient with a starting temperature of 570°C over the heated were. Laboratory experiments showed that the difference between the axial and radial design increased with temperature. With the radial design, a higher velocity of the air flow was created towards the center of the nozzle. The results show the importance of the angle when air flow is blown on an arc.

By heat distribution measurements, calculations of the convection loss over the heated wire during the cooling process were done. The convection loss increased with stepwise air flow and proved to be dependent on the air flow. The results verified the validation of the model. Hence, the convection loss can describe the efficiency of the cooling for the setup.

Simulations in COMSOL Multiphysics proved to be a good comparison to the laboratory experiments and a deeper picture of the heat distribution was analyzed. A good simulation model of the axial flow was obtained. Making a simulation model of the radial flow turned out to be more complex, but some results indicate the creation of turbulent flow with the radial design.

Sammendrag

Strømbrytning er en kompleks prosess, og optimalisere designet til lastbrytere er vanskelig. Dagens dominerende teknologi for lastbrytere på mellomspenningsnivå, er ved bruk av SF_6-gass som slukkingsmedium. Siden SF_6 er klassifisert som en drivhus gass med et veldig høyt globalt oppvarming potensial, har industrien begynt å se på andre metoder. Et interessant alternativ er å bruke luft som slukkingsmedium. Ved bruk av luft istedenfor SF_6, er optimalisering med tanke på størrelse viktig. På grunn av de gode egenskapene til SF_6 som slukkingsmedium, er det lite forskning med bruk av luft i lastbryter som har blitt gjort.

Denne masteroppgaven analyserer hvordan luftstrømmer skal konstrueres for å oppnå best mulig nedkjøling av en lysbue. En forenklet eksperimentelt laboratorietoppsett, basert på stabile luftstrømmer med en elektrisk oppvarmet wolframtråd, for å simulere en lysbue, ble brukt. To forskjellige luftstrømdesign ble laget og testet i laboratoriet, kalt aksiell og radiell strømming. Med det aksielle designet, ble luftstrømmen blåst rett på den oppvarmede tråden. Med det radielle designet, ble luftstrømmen blåst 90° på den oppvarmede tråden. To forskjellige tråddiametere ble brukt og testet, 0.15 og 0.38 mm. Det radielle designet viste seg å være 35% mer effektivt med en starttemperatur på 570°C. Laboratorieforsøk viste at forskjellen mellom aksiell og radiele blåsning økte med temperatur. Med radiell blåsing ble en høyere hastighet av luftstrømmer skapt mot sentrum for dysen. Resultatene viser viktigheten av vinkelen når luftstrømmer skal slukke en lysbue.

Ved målinger av varmedistribusjonen over den oppvarmede tråden, ble utregninger av konveksjonstap under nedkjølingsprosessen utført. Konveksjonstapet økte trinnvis med påført luftstrøm, og påført luftstrøm viste seg å være den avhengige faktoren for konveksjonstapet. Resultatene bekreftet gyldigheten av modellen. Dermed kan konveksjonstapet beskrive effektiviteten til nedkjølingen for oppsettet.

Datasimuleringer i COMSOL Multiphysics viste seg å være en god sammenligning til laboratorieforsøkene, og en dypere analyse av varmedistribusjonen ble oppnådd. En god simuleringsmodell av det aksielle designet ble utført . Å lage en god simuleringsmodell av den radielle strømningen viste seg å være mer komplekst, men resultatene som ble oppnådd antyder skapelse av litt turbulent strømning. Dette kan være med på å beskrive den mer effektive nedkjølingen ved bruk av radiellblåsning.

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Chapter 1

Introduction

Devices for making and breaking the electric current are essential to our electric power system. These components are typically referred to as switchgear, switches, or breakers. Generally speaking, switching equipment in electric power systems have two tasks: To open or close electrical connections, either as a planned change in the grid configuration or as an action to disconnect a faulty part of the grid from the rest. Hence, their ratings and requirements vary considerably.

The load-break switch (LBS) should be able to interrupt current less or equal to the load current, i.e. the maximum continuous current the system is rated for. This is used in medium-voltage (MV) distribution network, typically 6-36 kV, with a current up to 1000 A.

The dominating technologies for LBSs in MV switchgear is knife switching, using SF_6 as the interruption media and puffer switches, based of SF_6 and/or arc quenching materials. Vacuum interrupters are also used for interrupting load currents, but this is more expensive. SF_6 is classified as a potent greenhouse gas with very high global warming potential. Thus, the industry has begun looking at other technologies. One interesting option is to quench the arc using air. Air has a lot of physical properties that are well suited as an interruption media. However, the current interruption capability is better with the use of SF_6 and the problem is then to make air-filled switchgear as compact as today's SF_6 solutions [2] [1] [11].

In the specialization project, the experimental laboratory setup was made. This consisted of a simplified setup based on steady-state air flow with an electrically heated wire simulating the arc. Important factors as wire material, air flow designs and measurement method were determined. Experiments were tested using a wolfram wire with a diameter of 0.25 mm, finding the relationship between the current and temperature, and also how the designs influenced the cooling.

In the master thesis, further work on the experimental setup will be done. Different wire diameters will be tested to see how this affects the cooling. Also, different wire locations will be tested to give a better understanding of the air flow during arc cooling. The goal is to determine how the air flow should be designed to obtain the best interruption performance. These experiments will be compared up to a simulation model made in the finite element method (FEM) software COMSOL Multiphysics, where deeper analysis of the heat distribution along the simulated arc can be obtained.

The structure of this thesis is as follows: Firstly, there is an introduction to the theory behind the experiments: current interruption, air flow and heat transfer. Then, a description of the experimental setup, measurement methods and an interpretation of the measurements is presented in Chapter 3. In Chapter 4 the results of laboratory experiments are presented. Next, in Chapter 5, the building of the COMSOL model is explained. Furthermore, the simulation results are presented in Chapter 6. The final chapters, Chapter 7 and Chapter 8, contain a discussion of the results and a conclusion, together with suggestions for further work.

Chapter 2

Theory

This chapter primarily consists of the current interruption process and heat transport in electric arcs for switchgear. This is the underlying theory behind the experiments that have been done.

2.1 Switchgear

Switching equipment can be divided into four categories:

- ***Earthing switches***, used to earthen or ground parts of the grid.
- ***Disconnecter switches***, opens the circuit when is its energized, but does not carry load and short circuit currents.
- ***Load break switches***, interrupts currents less or equal to the load current. They are to a large extent used in the MV level, normally from 6 to 36 kV, and with currents variating from 400 to 1000 A. The load break switch and disconnecter switch functions are often combined into one device, where fuses are used in series with this device for interrupting short circuits. The device is often called a *switch-disconnecter*.
- ***Circuit breakers***, which have the most demanding task and should interrupt all currents that may occur at the position where it is installed. They are very important for clearing faults in the grid, normally for voltages greater than 36 kV. Compared to load break switches, circuit breakers are very expensive [8].

2.1.1 Requirements

Load break switches and circuit breakers must fulfill certain requirements, regardless of the field operations, as it is stated in [6]:

- When closed, it must be an almost perfect conductor.
- When open, it must be a perfect insulator.
- When closed, it must at any time be able to interrupt any currents that may occur, without generating unacceptably large over-voltages.
- When open, it must at any time, including when short circuit currents pass, be able to close the contacts without them together (as this would prevent the breaker from being able to open at a later occasion).

These requirements may be demanding, and the emphasis put on the different requirements may vary with the breaker application.

2.2 Current interruption

A switching device contains pairs of contacts in each phase. To interrupt the current, the contacts separate and move away from each other. Influenced by this an arc is created. The arc continues to carry the current through a plasma, which is a mixture of electrons, neutral particles and positive and negative ions. The temperature of the plasma is very high due to the energy dissipated in the arc by the current flow. To interrupt the current, applying forced cooling in addition to separating the contacts is required.

The working principle of a switching device is essential to cool the electric arc so efficiently that it becomes virtually insulating as the current reaches zero, and then to quench the arc and interrupt the current at this moment. After the arc has been quenched at current zero, a voltage builds up across the open contacts. This is called recovery voltage. Fig. 2.1 illustrates the current through the breaker and the voltage drop across the contacts during an interruption process. The amplitude and steepness of the recovery voltage determine whether a new arc ignites after current zero: i.e. if the current interruption has been successful or not. If a new arc is developed after current zero, a re-ignition occurs.

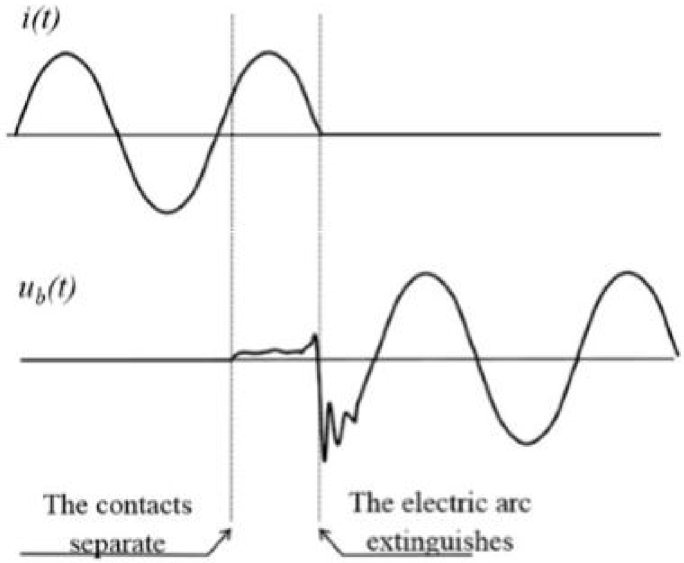


Figure 2.1: Current and voltage during a current interruption[6].

Re-ignition is divided into two categories: thermal and dielectric re-ignitions. Thermal re-ignition is caused by thermal instability in the electric arc, while a dielectric re-ignition occurs if the recovery voltage at any time exceeds the dielectric strength of the contact gap. If a new arc occurs at a quarter of a power cycle or more after a current zero crossing, its called a re-strike[8] [6].

2.2.1 Interruption media

When interrupting the current, the interruption media is important. Vacuum and SF_6 gas are the dominating interruption medias today, but they have some drawbacks. Vacuum interrupters are expensive and SF_6 is a strong "greenhouse" gas. On the basis of this, the industry is looking for other technologies.

Air contains almost 80% nitrogen. Thus, properties for N_2 are interesting when considering air as an interruption medium. Nitrogen has a low critical temperature (126 K) and pressure (33.5 bar). For lower currents, the ionization molecule for nitrogen is larger than for free atoms. The change from conducting to insulating state becomes more clear on the basis of this. N_2 decomposes in the range of 4.000-10.000 K, meaning the ionization starts at these temperatures and the gas changes from being insulating to conductive at approximately the same temperature. At high currents the electric conductivity is good, and consequently, the arc voltage is low due to the dissociation energy for nitrogen. With SF_6, the arc voltage is even lower[8].

SF_6 gas also has better dielectric strength and interruption medium than air. In the interruption process, two properties are desirable. Firstly, the thermal properties of SF_6 are beneficial in the thermal interruption. It can absorb and transport large quantities of energy at the temperatures relevant to current interruption, due to the process of dissociation and recombination of molecules. Secondly, the high breakdown strength of SF_6 is beneficial to withstand the transient recovery voltage. The breakdown strength is high due to the size/weight of SF_6 molecules and its electro negativity.

Nevertheless, the physical properties that are important in the present context are fairly good for air/N_2. They are non-toxic, incombustible, non-corrosive, inexpensive and have definitely no negative environmental properties. Regardless, this gives challenges both in the dielectric design of the switchgear and both the arc quenching and current interruption capability with the use of air [8].

2.3 Air flow

Air flow is caused by a pressure difference between two points. The air flow will originate from a point of high pressure, and proceed to a point of lower pressure. Air flow can be defined into two types of motion:

- Laminar flow
- Turbulent flow

In laminar flow, the motion of the particles of a fluid is very orderly with all particles moving in straight lines parallel to the object. In contrast, turbulent flow is characterized by chaotic changes in pressure and flow velocity. In general, laminar flows happen when dealing with smaller areas and low flow velocity, while turbulent flow happens at higher flow rates and in larger areas. The interrupting ability of an arc is greatly improved by turbulent motions.

The cooling of the arc and thus the interrupting capability are greatly influenced by the air velocity and flow pattern as well as contact, nozzle, geometry and dimensions. Heat transfer is an important factor when looking at the flow pattern and the cooling of the arc, thus how the exchange of thermal energy in a system [3] [12].

2.4 Heat transport in Electric Arcs

Heat transfer, the flow of energy in the form of heat, is a process by which a system's internal energy is changed. To be able to change the electrical conductance of a high-pressure switching arc suddenly near current zero, the temperature of the arc has to be reduced drastically. Accordingly, cooling of the arc channel is managed in different ways and various power switching components. This shows the relevance of heat transfer mechanism in high pressure switching arcs. In heat transfer, the three fundamental modes of heat transfer are conduction, radiation and convection [6].

2.4.1 Heat conduction

Energy transfer by heat conduction can be thought of as the energy transfer from the more energetic particles of an object to nearby particles that are less energetic, due to interactions between particles. This means the heat energy moves from high temperature to the low temperature. The collision with the surrounding atoms and molecules transfers heat energy to the others such that, the heat is more evenly distributed. By Eq. (2.1) the rate of heat transfer across any plane normal to the x direction, Q_x, is proportional to the wall area, A, the thermal conductivity of the material,k, and the temperature gradient in the direction, $\frac{dT}{dx}$ [5].

$$Q_x = -kA\frac{dT}{dx} \tag{2.1}$$

2.4.2 Radiation

Thermal radiation gives off heat by matter as a result of changes in the electronic configurations of the atoms or molecules within it. The energy is transported by electromagnetic waves. Unlike thermal conduction, thermal radiation requires no intervening medium to propagate. All different heated solids or objects emit, absorb, and transmit thermal radiation at different degrees. The rate of which energy is emitted, Q_e, from a surface of area A is quantified macroscopically by a modified form of the Stefan-Boltzmann law, $\sigma = 5.6703*10^{-8} W/m^2K^2$, showed in Eq. (2.2). Where ϵ is the emissivity of the surface of the material and T the surface temperature [5] [6].

$$Q_e = \epsilon\sigma AT^4 \tag{2.2}$$

Radiation is of great importance for the energy transport within an arc. Plasma in an arc emit or absorb radiation through several different processes. These can be grouped into two categories:

- Radiation from atoms going from one energy level to another.
- Radiation from charged particles that are accelerated.

2.4.3 Convection

Convection is the transfer of heat from one place to another by the movement of fluids. This is often the dominant form of heat transfer in liquids or gases. Convection can be defined in two different types:

- Free convection.
- Forced convection.

Free convection occurs whenever a body is placed in a fluid at higher or a lower temperature than that of the body. As a result of the temperature difference, heat flows between the fluid and the body and causes a change in the density of the fluid layers in the vicinity of the surface. The difference in density leads to a downward flow of the heavier fluid and upward flow of the lighter. If the motion of the fluid is caused slowly by differences in density resulting from temperature gradients, without the aid of a pump or fan, the associated heat transfer mechanism is called natural or free convection [4].

In switchgear, convection appears when air flow is blown against the arc from an external source, extinguishing the arc at current zero. This is called forced convection or forced cooling. Hence, convective cooling is closely related to flow of gases. High convection, therefore, results therefore in better cooling of the arc. The rate of energy transfer from the surface to the air can be quantified by Eq. (2.3). Where h is the heat transfer coefficient of the process, A the heat transfer area of the surface, T_b the maximum temperature over the material and T_f the minimum temperature over the material [5] [6].

$$Q_c = hA(T_b - T_f) \tag{2.3}$$

2.4.4 Temperature Distribution in an Electric Arc

The detailed expertise concerning temperature distribution inside the arc of a switching device is far from complete, but a good semi-quantitative understanding exists. The temperature contour through the cross-section of the arc is approximately bell-shaped at low currents, with the highest temperature in the center. As long as the currents are relatively low, the maximum temperature, and thereby the conductance of the arc, follows changes in the amplitude of the current during a power cycle [6].

If the current is increased, the temperature does not rise without limits. At 20 000 - 30 000 K, the radiation losses from the arc are so great that the temperature and electric conductivity varies relatively little with the radial distance. Increasing the current even further only increases the arc cross-section, talking about several thousand amperes. Hence, in general terms, at low currents the arc temperature changes with changes in the current. On the other hand, large currents the maximum temperature is fairly constant across the cross-section [6].

By investigating the heat transfer over the heated wire, information on how efficient the cooling of the simulated arc is given. This helps to obtain a better understanding of the different air flow designs which are tested, considering the method used in this thesis.

Chapter 3

Method for experimental measurement

This chapter presents the setup and different components of the test circuit used in the laboratory, together with the measurement method.

3.1 Experimental setup

A simplified experimental setup was made to better understand how the cooling of the arc is influenced by the air flow. The laboratory setup is based on steady-state air flow with an electrically heated current carrying conductor simulating an arc. This is also known as *joule heating*. In equilibrium, the temperature of the wire would be balanced by heat loss and heat transport. The heat loss depends on the flow rate, the heat conductance coefficient of the wire material and the temperature difference between the wire and the surrounding air. The measurement method and wire material were decided in the specialization project for this master thesis [7].

Wolfram was selected as the wire material for the conductor simulating an arc. Wolfram has the highest melting point (3422°C) and lowest vapor pressure of all pure metals. It has a resistivity, ρ_0, of $5.60 \cdot 10^{-8}$ (at room temperature), and a temperature coefficient, α, of 0.0046 per °C. Wolfram also has excellent corrosion resistance and is only attacked slightly by most mineral acids. These relevant properties make it desirable to the purpose of the intended experiments, carrying currents and creating high temperatures without melting [9].

In the laboratory setup, a 5 cm long wolfram wire was used during the joule heating. In the specialization project, a wolfram wire with a diameter of 0.25 mm was tested [7]. In addition to this, two dimensions with diameters 0.15 and 0.38 mm are tested in the thesis. It is desirable to see if the cross-section of the wires has some impact on the cooling over the simulated arc. Table 3.1 shows the cross section, surface area and resistance for the three different dimensions at ambient temperature. Due to the positive α (temperature coefficient) of wolfram, the resistance of the wire will increase at higher temperatures.

Table 3.1: Wolfram properties for the relevant wire diameters with a length of 5 cm.

Diameter $[mm]$	Cross section $[mm^2]$	Surface area $[mm^2]$	Resistance $[\Omega]$
0.15	0.018	23.562	0.1584
0.25	0.049	39.270	0.057
0.38	0.113	59.690	0.0247

3.1.1 Wire location

When cooling an arc the ionized air will move around while air flow is applied. Hence, the air flow is not always blown straight on the arc. Considering this, air flow experiments were executed with the simulated arc placed at different locations to see how the air flow affects the cooling. This gives information about where air flow has the highest velocity over the simulated arc.

Five different placements were tested, including the middle placement used in the standard measurements. Fig. 3.1 displays the wire placements during the cooling process.

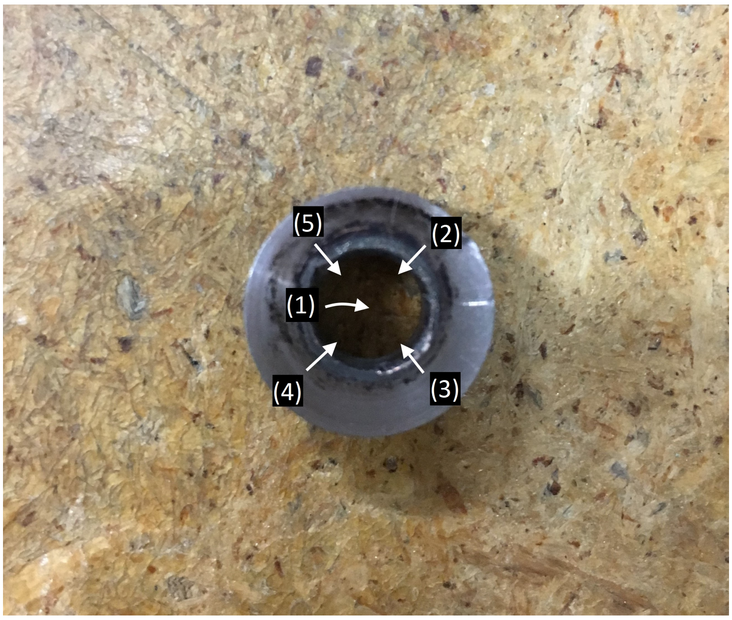


Figure 3.1: Placement locations for the wolfram wire during the laboratory experiments.
(1) Middle, (2) Top right, (3) Down right, (4) Down left, (5) Top left.

3.1.2 Test circuit

The test circuit used in the laboratory is illustrated in Fig. 3.2. The current source with a range of 0-10 A applies current through the wolfram wire, working like a resistance and generating heat. The voltmeter is used to measure the voltage over the heated wire, which is further used to find the temperature over the wire. An ampere-meter was also used measuring the true current going through the circuit.

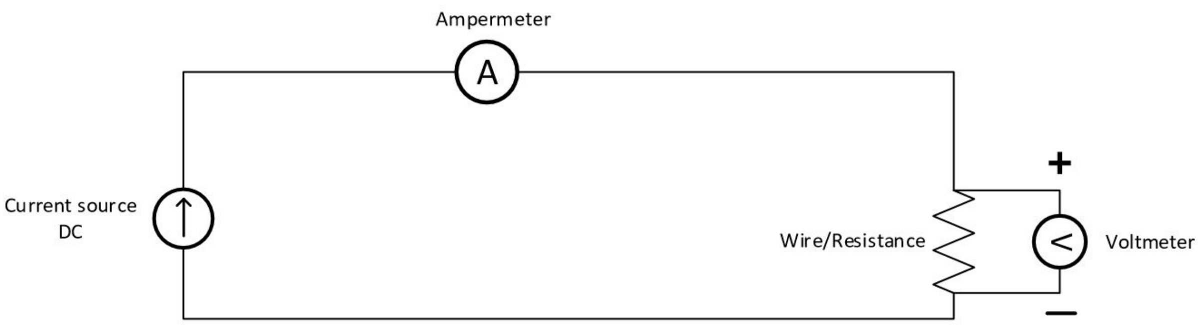


Figure 3.2: Test circuit used in the laboratory experiments.

Fig. 3.3 shows the setup in the laboratory. As mentioned, the current source to the left applies current through the wire, placed in the middle of the test circuit. Air flow is blown through the nozzle, from the air generator behind the test circuit. The amount of air flow is selected from the air flow controller, connected to the generator. Air flow was received from a compressed air tank in the laboratory. The component models and serial numbers can be seen in appendix C.

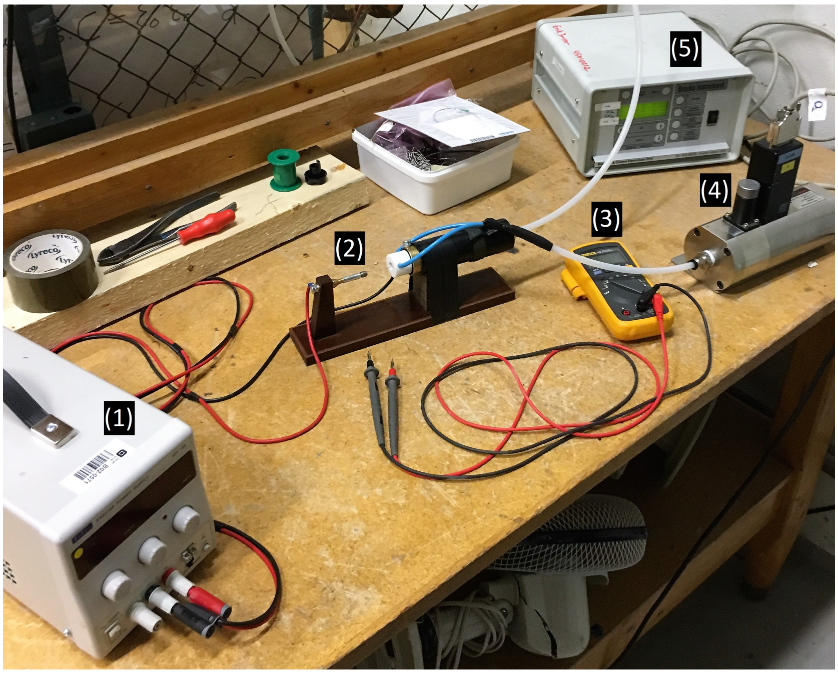


Figure 3.3: Laboratory setup. (1) Current source, (2) Test circuit, (3) Multimeter, (4) Air flow generator and (5) Air flow controller.

The nozzle was made of the insulating material, teflon (PTFE). The nozzle has a length of 2.1 cm and a diameter of 4.7 mm to control the direction of the fluid flow. See Fig. 3.4. In order to achieve the correct and efficient air flow on the burning arc, the nozzle design is very important.

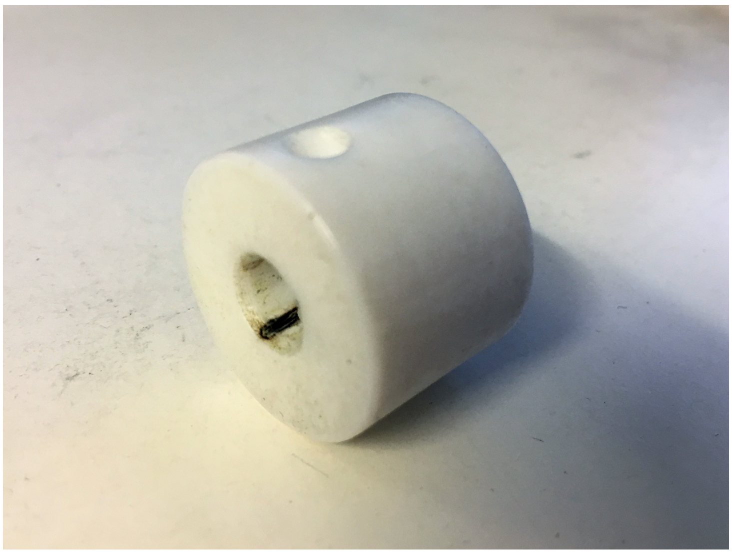


Figure 3.4: PTFE nozzle used inn all laboratory experiments.

The air flow generator has a range of 0-500 ln/min. The unit, ln/min, stands for liter normal per minute. This is a unit of volumetric flow rate of gas with 0°C and 1.013 bar as reference point. By using the air flow generator, the amount of air flow needed to effectively cool down the simulated arc can be accurately measured. Two different air flow designs were compared to see how the angle of the air flow affects the quenching of the simulated arc.

In the first design, *axial flow*, the air flow blows straight on the wire through the nozzle. This is illustrated in Fig. 3.5.

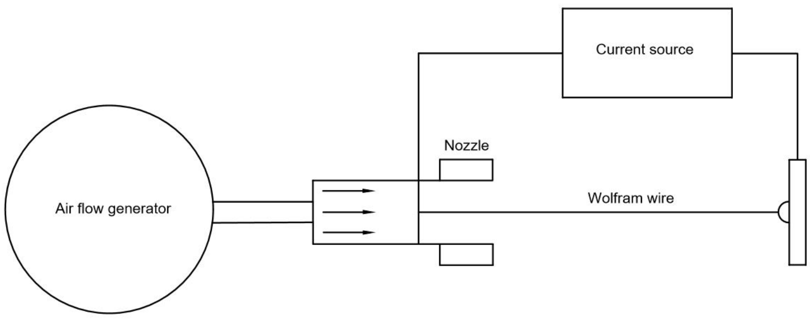


Figure 3.5: Axial flow design.

In the second design, *radial flow*, the air flow blows 90° onto the wire. Two holes were made on the nozzle such that two air tubes can blow onto the wire. One of the holes is shown in Fig. 3.4. Fig. 3.6 illustrates the radial design.

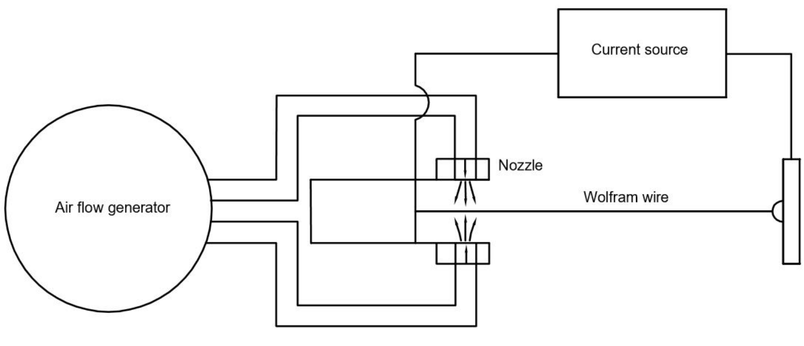


Figure 3.6: Radial flow design.

3.2 Measurement method

By deducing a relationship between voltage and temperature, accurately temperature measurements over the wire could be provided. This also gave the opportunity to measure the temperature over different areas of the simulated arc, giving information on how the heat was distributed.

Firstly, ohm's law, Eq. (3.1) is presented and placed into the formula for resistance of a conductor, giving Eq. (3.2).

$$R = \frac{U}{I} \tag{3.1}$$

$$\frac{U}{I} = \rho \frac{l}{A} \tag{3.2}$$

Eq. (3.2) is further placed into the formula for temperature changes of a resistance, Eq. (3.3)

$$\frac{U}{I} = \rho \frac{l}{A}[1 + \alpha(T - T_0)] \tag{3.3}$$

In Eq. (3.4), Eq. (3.3) is altered giving an easier expression. $(T - T_0)$ is expressed as ΔT.

$$\frac{UA}{I\rho l} = 1 + \alpha \Delta T \tag{3.4}$$

At last, deducing the formulas, the final equation, Eq. (3.5) is given, expressing ΔT, the temperature over the wire.

$$\Delta T = \frac{1}{\alpha}(\frac{UA}{I\rho l} - 1) \tag{3.5}$$

Eq. (3.5) shows that the temperature over the wire, ΔT, is influenced by:

- α, the temperature coefficient of wolfram.
- U, the measured voltage over the wolfram wire.
- A, the area of the wolfram wire.

- I, the current from the current source.
- ρ, resistivity of the wolfram wire.
- l, the length of the wolfram wire in the test circuit.

3.3 Convection loss

The convection loss is an indicator of the cooling efficiency. To calculate this, the power P_{in} and P_{out}, had to be found. This is an approach to examine the validation of the method. Accordingly, the convection loss should be independent of the wire diameter.

The input power, P_{in}, equals $U \cdot I$. To find the output power, P_{out}, the three different heat transfer modes: conduction, radiation and convection needed to be considered. The respective Eqs. for these, ((2.1), (2.2), (2.3)), are mentioned in Chap. 2.4.

To calculate the convection loss, the formulas were first set up in the original way, Eq. (3.6). P_{in} is set equal to P_{out}, as no temperature change is assumed in steady state.

$$P_{in} = P_{cond} + P_{rad} + P_{conv} \tag{3.6}$$

Secondly, the formulas were altered to get the convection, P_{conv} alone, Eq. (3.7).

$$P_{conv} = P_{in} - P_{rad} - P_{cond} \tag{3.7}$$

When setting the expression for dT/dx, it is assumed that the temperature varies linearly, Eq. (3.8). Where T_2 is the maximum temperature over the wire, T_1 the minimum temperature over the wire and l the length of the wolfram wire.

$$\frac{dT}{dx} = \frac{T_2 - T_1}{l} \tag{3.8}$$

The final expression for the convection loss was then given in Eq. (3.9), with the formulas mentioned in Chap. 2.4 [10].

$$P_{conv} = UI - \epsilon\sigma A_s(T^4 - T_0^4) - kA_{cs}\frac{T_2 - T_1}{l} \quad (3.9)$$

The equation for convection loss, Eq. (3.9), is influenced by the parameters showed in Table 3.2. The current is adjusted with the current source, and the voltage is affected by the current over the wire and the diameter of the wire. The cross-section of the wire is implemented in the conduction part, and the surface area in radiation.

Table 3.2: Parameters for convection loss calculations.

Name	Expression	Description
U	0-3 [V]	Measured voltage over wire
I	0-10 [A]	Injected current
l	50 [mm]	Length of wire
d	0.15,0.25,0.38 [mm]	Diameters of wire
T_0	293.15 [K]	Ambient temperature
T_1	293.15-873.15 [K]	Measured temperature over the wire, min
T_2	293.15-873.15 [K]	Measured temperature over the wire, max
k	173 [W/mK]	Thermal conductivity of wolfram
σ	$5.6703 * 10^{-8} [W/m^2K^4]$	Stefan-Boltzmann constant
ϵ	0-1 []	Emissivity
A_{cs}	$\left(\pi\frac{d}{2}^2\right) [m^2]$	Cross-section of wire
A_s	$\pi d l \ [m^2]$	Surface area of wire

3.4 Interpretation of measurements

Because the industry is looking for other quenching technologies, properties of air, how it works and the most effective ways of using it are very relevant. The purpose of the laboratory experiment, heating up a wire with a current, is to simulate an arc in a switch. The main focus is the cooling and heat distribution of the simulated arc. The cooling and thus the interrupting capability are greatly influenced by the air velocity and flow pattern, as well as contact and nozzle geometry and dimensions. By testing and comparing different air flow designs, important properties of air as an interruption media can be compared and determined.

When using a wire to simulate an arc, it is important to consider the difference between cooling a wire compared to a plasma. The wolfram wire is attached in a stable setup, while when cooling a plasma, the ionized air will move around when applied air flow. This must be taken into account when analyzing the experiments and comparing with what really happens when cooling an arc in current interruption. As a result of this, the radial design can be looked upon at a more realistic picture, where air flow is blown around the arc. With the axial flow, the arc would be pressed against the wall and therefore gives more insecure results considering the interpretation of the measurements.

Chapter 4

Laboratory results

In this chapter, the results from the work conducted at the laboratory are presented. Two different diameters of the wolfram wires were used, 0.15 and 0.38 mm. All the test were done with the axial and radial design, together with measurements of the heat distribution and convection loss calculations.

4.1 Temperature influenced by current

The first step in the laboratory was to find the relationship between the current and the temperature for the two different wire dimensions, without any forced flow. Accordingly, the wire was heated up by a stepwise current and thus the voltage measured to find the temperature over the simulated arc, using Eq. (3.5).

Fig. 4.1 illustrates the temperature increasing for the wolfram wire with a diameter of 0.15 mm. As seen, the heating went slowly up to 1.5 A where it reached 100°C. From 1.5 to 2 A, the temperature tripled to 300°C. From 2 to 3 A, the temperature had a continuance rise up to 1050°C. This was the maximum temperature reached without the wire melting.

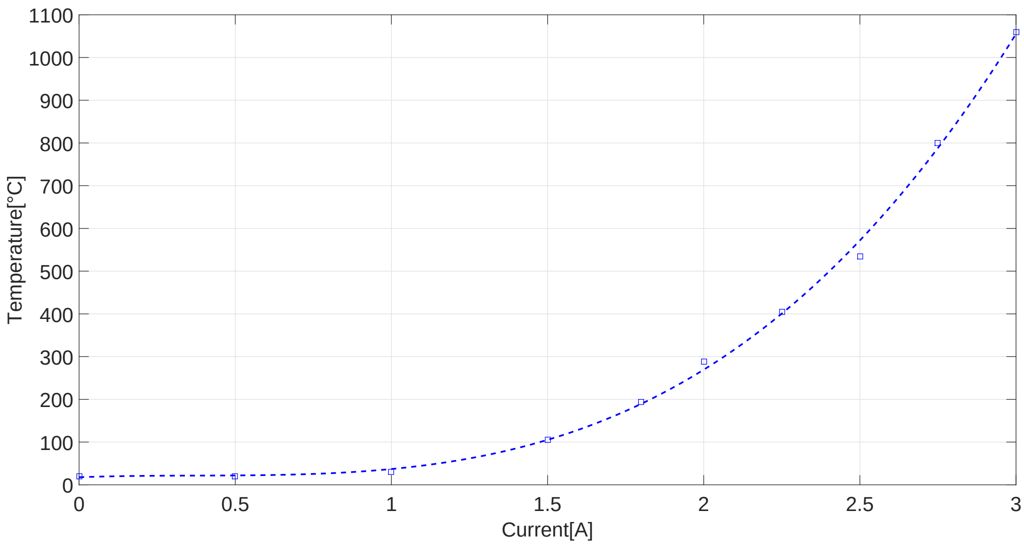


Figure 4.1: Temperature influenced by current over a wolfram wire with a diameter of 0.15 mm.

Fig. 4.2 illustrates the temperature increasing for the 0.38 mm wolfram wire. The current seemed to have a very small influence of the heating up to 5 A. At 6 A the wire almost reached a temperature of 100°C. From 6 to 10 A the temperature had a stable increasing up to 570°C. This was the maximum temperature reached with the 10 A current source.

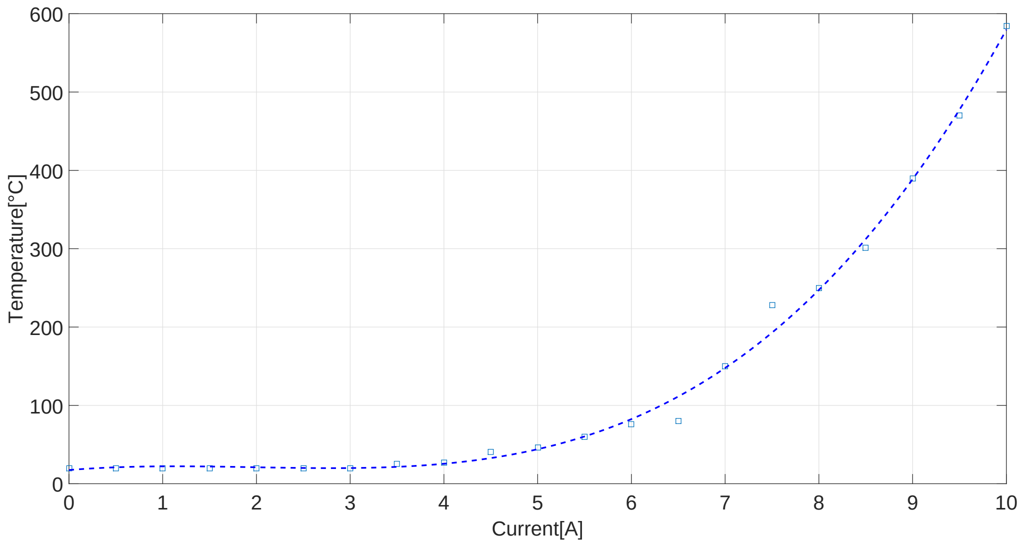


Figure 4.2: Temperature influenced by current over a wolfram wire with a diameter of 0.38 mm.

In the further experiments, the intension was to find approximately the same temperature for the two wire dimensions and compare the temperature cooling, heat distribution and convection loss between the dimensions. Hence, examine if the dimensions of the wires were independent of the temperature cooling. This is a way to examine if the convection loss is independent on the wire, and accordingly the validation of the model.

4.2 Axial flow

In the experiments with forced air flow, the axial flow design was first investigated. As illustrated in Fig. 3.5, the air flow was blown straight on the wire.

4.2.1 Standard measurements

Firstly, standard measurements were done with the axial flow, i.e. the wolfram wire placed in the middle location during the cooling process. See Fig. 4.3.

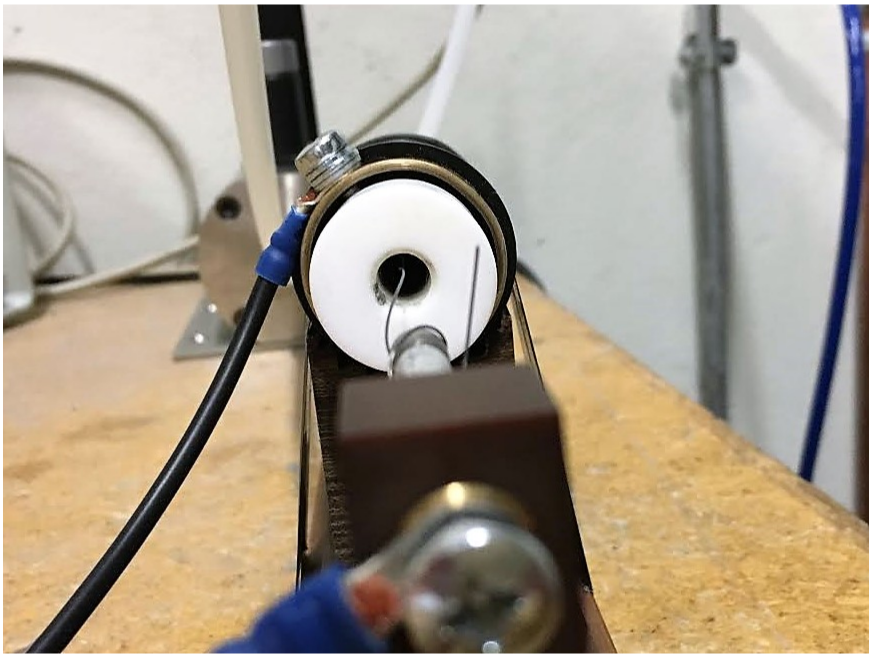


Figure 4.3: Middle placement of the wolfram wire in the laboratory experiments.

The intention was to simulate air flow blown straight on an arc. Fig. 4.4 shows the cooling of the heated 0.15 mm wire with a starting temperature of approximately 560°C. The cooling almost held a linearly negative trend. For each air flow step, the simulated arc was approximately decreased with 100°C. By blowing an air flow of 68 ln/min the temperature was almost halved. But as results from the specialization project showed, with higher air flows, the cooling happened slower[7]. With 250 ln/min, the simulated arc was successfully cooled down to the ambient temperature of 20°C.

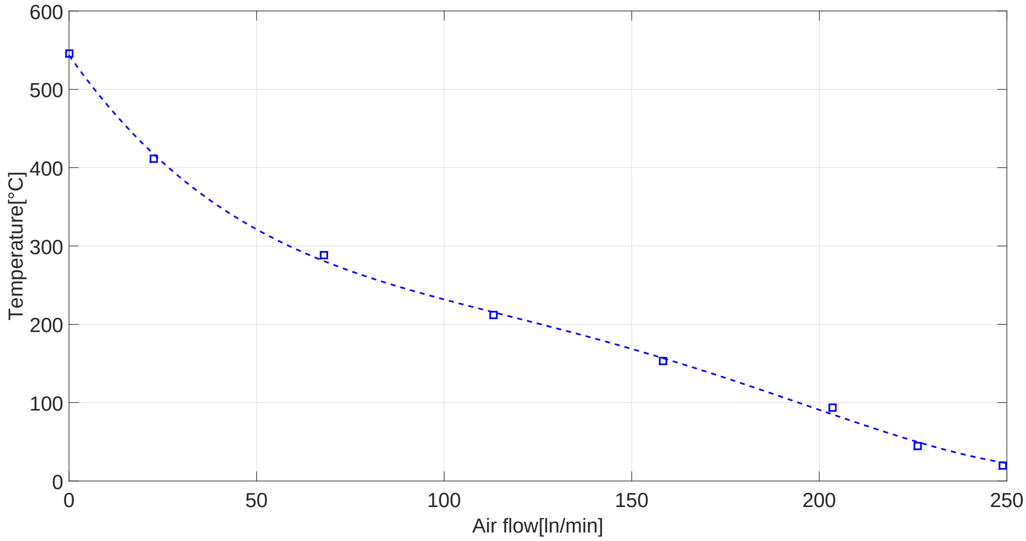


Figure 4.4: Axial flow over a wolfram wire with a diameter of 0.15 mm and a starting temperature of 560°C.

Next, the same experiment was done with the 0.38 mm wolfram wire. See Fig. 4.5. Almost the same pattern as in Fig. 4.4 was observed, with a linearly negative trend. The temperature was approximately halved with 68 ln/min, and the simulated arc was successfully cooled down to the ambient temperature, 20°C, with 250 ln/min.

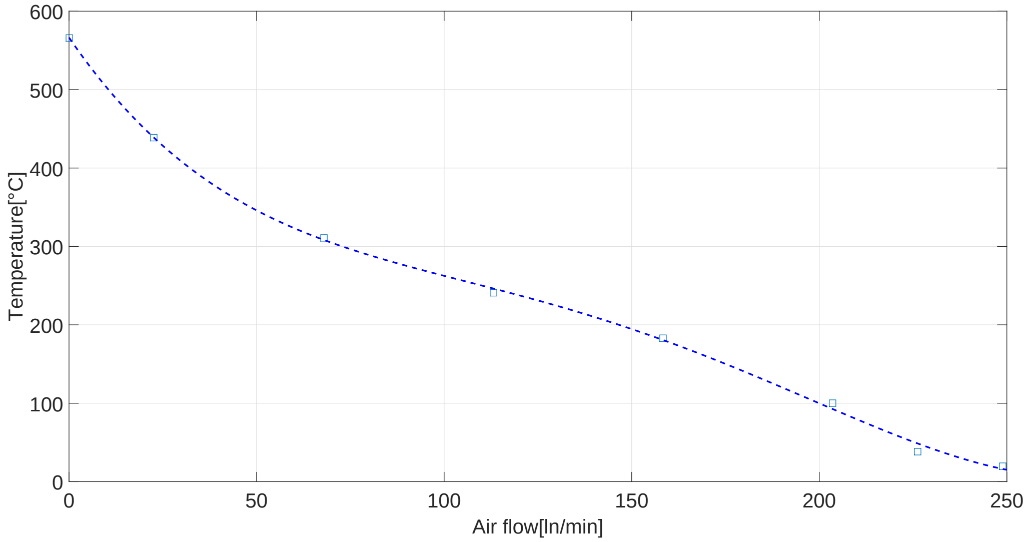


Figure 4.5: Axial flow over a wolfram wire with a diameter of 0.38 mm and a starting temperature of 570°C.

As observed from Fig. 4.4 and Fig. 4.5, the diameter of the wire seemed to have no influence of the cooling for the axial design. The needed amount of air flow to cool down the simulated arc were equal for the two different diameters. Hence, the needed air flow to cool down the wire to the ambient temperature is not dependent on the thickness of the wire, but only on the amount of air flow blown onto the simulated arc.

4.2.2 Placement of wire

Fig. 4.6 shows the four different placements of the wolfram wire in the experiments done in the laboratory, excluding the middle placement. As seen, Fig. 4.6 illustrates the different wire placements with the radial design, but the same positions were used for the axial design. These four placements, together with the middle placement, contributes to a comparison of the air flow from the nozzle. When a load switch break quenches the arc, the air flow is usually not blown straight on the wire. Thus, it is possible to get information about where the velocity of the air flow is highest out from the nozzle.

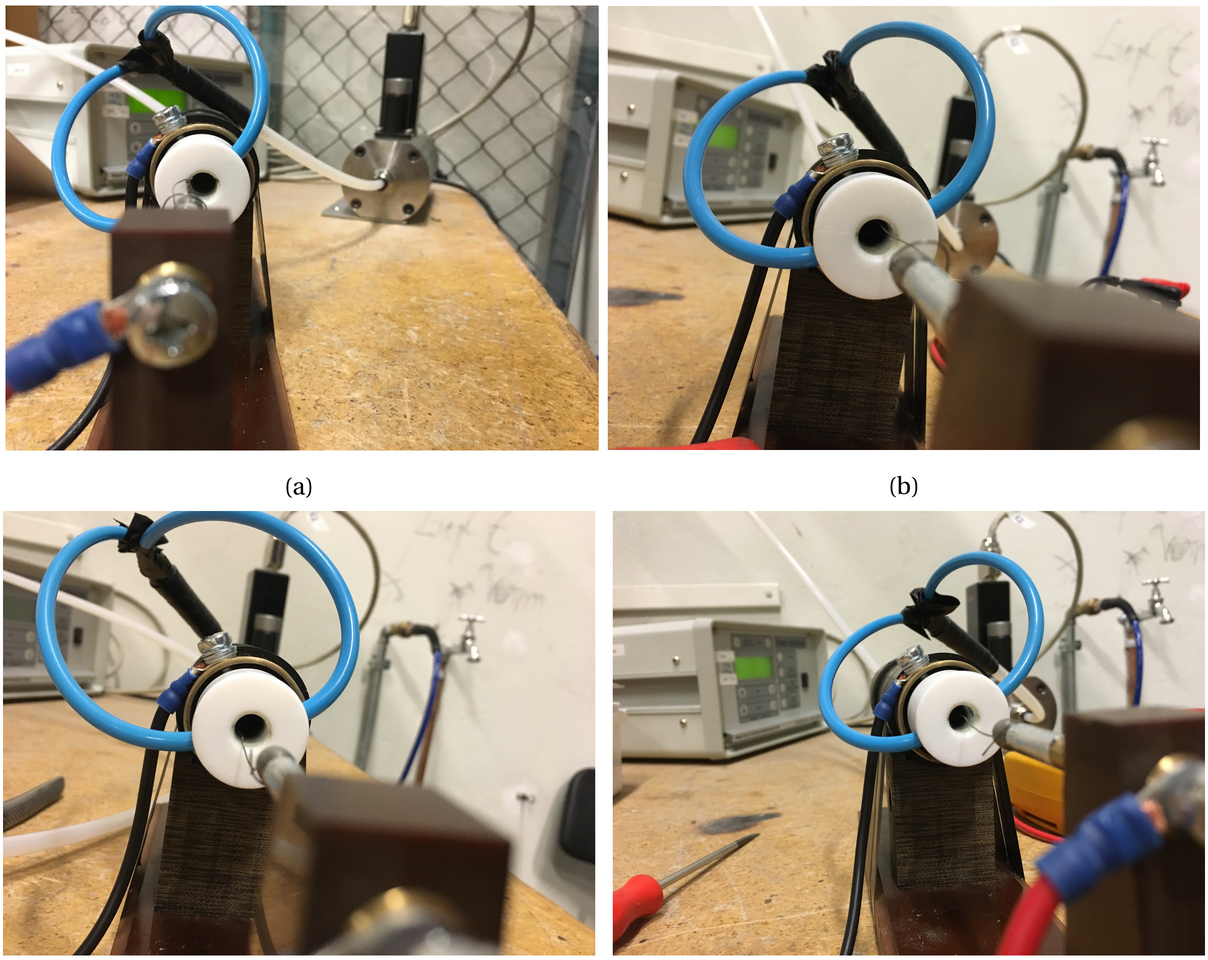


Figure 4.6: Different placements of the wolfram wire in the laboratory experiments. (a) Top left, (b) Top right, (c) Down left and (d) Down right.

For all five placements, the same applied current and the same amount of air flow were tested. Fig. 4.7 displays the five different wire regions tested, as shown in Fig. 3.1.

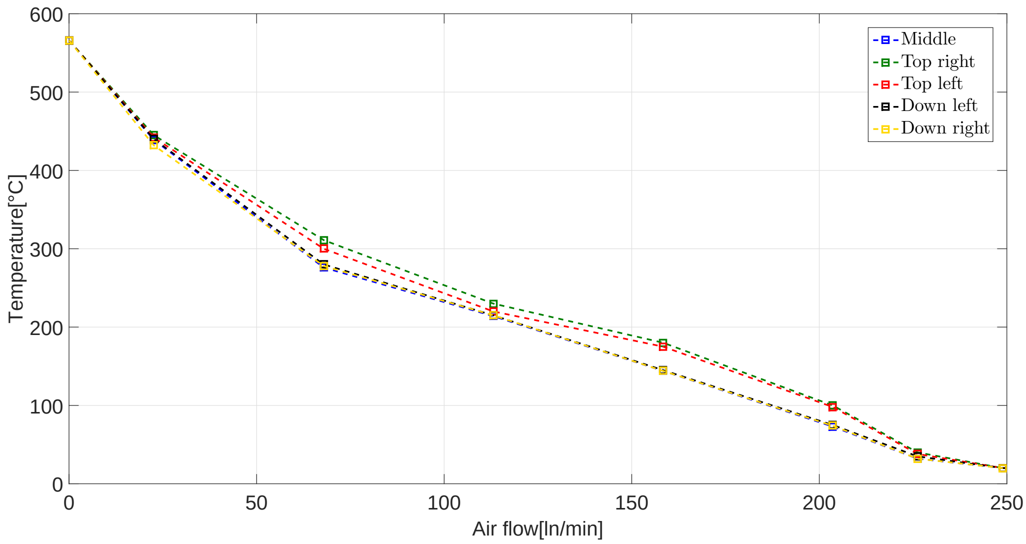


Figure 4.7: Axial flow over the wolfram wire at different placements.

The placement turned out to have no special influence of the cooling with the axial design. Some difference in the cooling was noticed, but the same amount of air flow was needed to cool down the arc for all locations.

4.3 Radial flow

Next, experiments with the radial flow design were investigated. As illustrated in Fig 3.6, the forced air flow was blown 90° onto the wire.

4.3.1 Standard measurements

As with the axial design, experiments with the wolfram wire located in the middle were first performed. Fig. 4.8 shows the cooling of the simulated arc with a diameter of 0.15 mm. The temperature over the simulated arc was almost halved by blowing an air flow of 22.6 ln/min. Further, the temperature held an almost linearly negative trend where the cooling effect decreased compared to in the beginning of the cooling process. The simulated arc was successfully quenched by an air flow of 159 ln/min.

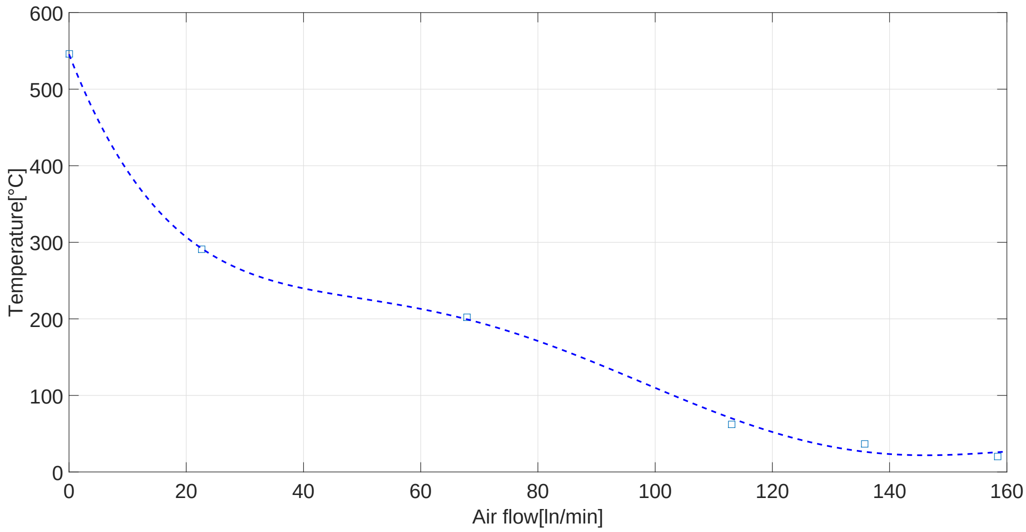


Figure 4.8: Radial flow over a wolfram wire with a diameter of 0.15 mm and a starting temperature of 560°C.

Next, the wolfram wire with a diameter of 0.38 mm was tested. Fig. 4.9 shows the cooling of the simulated arc. A forced air flow 22.6 ln/min did not seem to have the same amount of effect over the wire with almost 100°C more compared to the 0.15 mm. Further, the temperature had a stable reduction and was efficiently quenched with 159 ln/min. That is the same amount as for the 0.15 mm diameter.

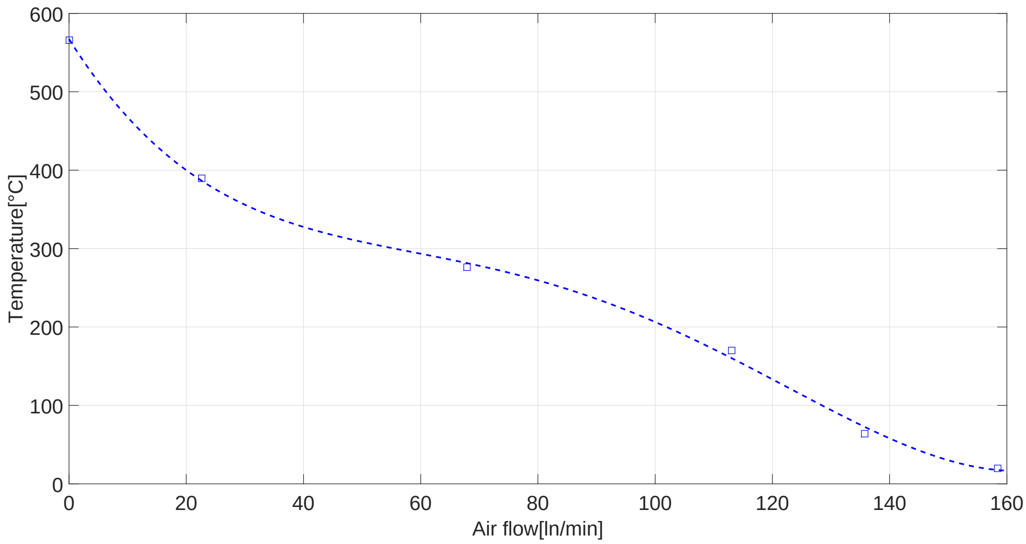


Figure 4.9: Radial flow over a wolfram wire with a diameter of 0.38 mm and a starting temperature of 570°C.

Figs. 4.8 and 4.9 shows that the dimensions of the wolfram wires used had no actuating influence on the cooling. Even though the trend varied for the two diameters, the same amount of air flow was required. This is also shown in appendix B.1, where results with a starting temperature of 488°C over both wire diameters gave the same indications.

4.3.2 Placment of wire

In Fig. 4.10, cooling of the simulated arc at the different placements with the radial flow are presented. The blue line presents the cooling of the wire placed in the middle, as in Fig. 4.9. As mentioned, 159 ln/min was needed to quench the simulated arc. With the four other placements, the cooling affected differently. They all needed an extra air flow of approximately 15-20 ln/min. At 22.6 ln/min almost the same cool-down was observed, but for the next steps the middle placement had more efficient cooling and quenched the simulated arc with less air flow.

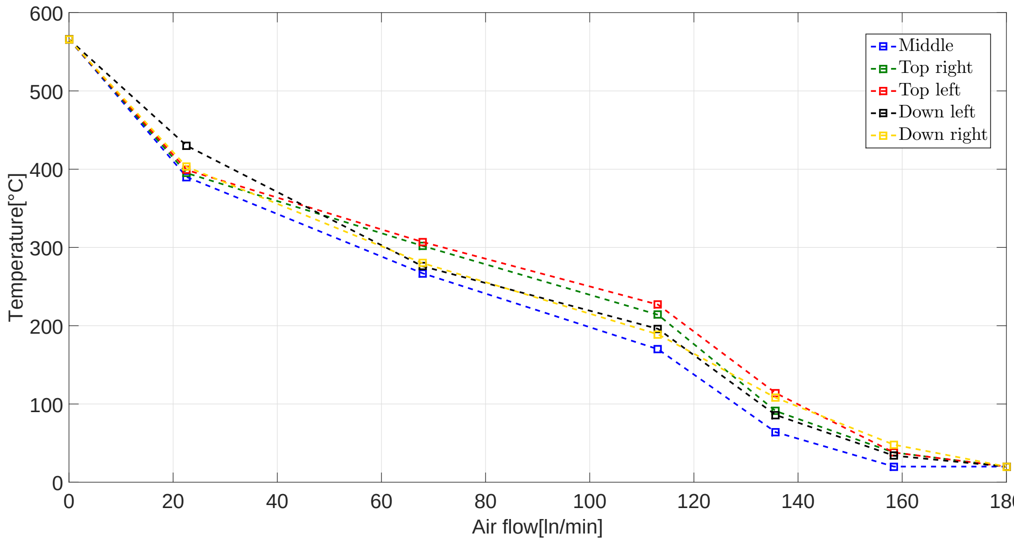


Figure 4.10: Radial flow over the wolfram wire at different placements.

4.4 Heat distribution

By knowing the heat distribution over the simulated arc at the different air flow levels, calculations of the convection loss can be performed. Hence, point measurements over the wire were done. Fig. 4.11 displays the three measurements that were done for different temperatures. As illustrated: (1) is at the connection end, (2), in the middle of the wire and (3), close to the teflon nozzle.

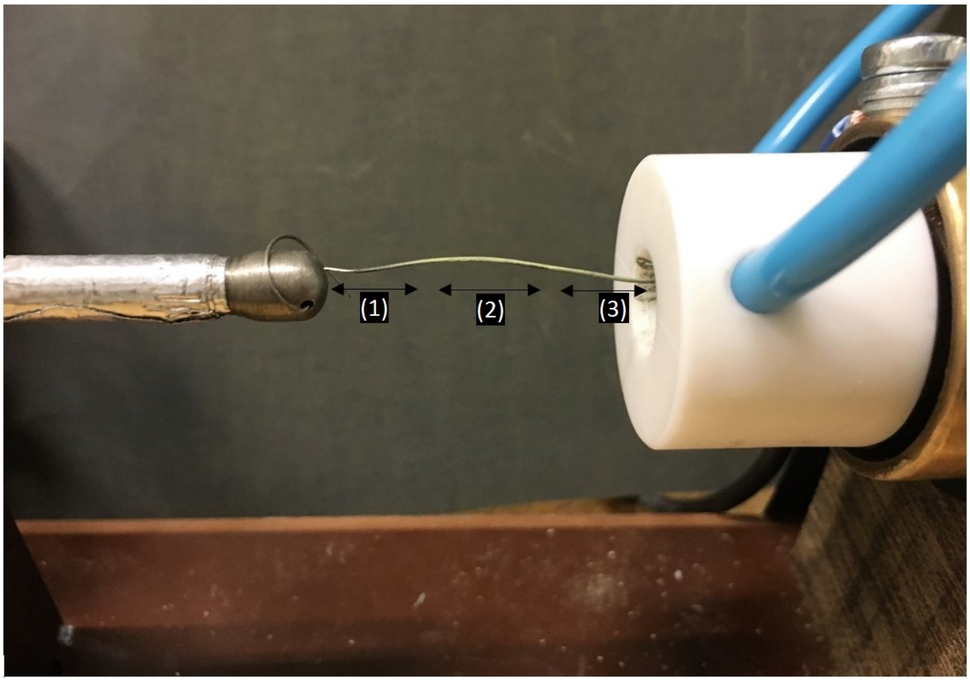


Figure 4.11: Illustration of the different points measured in the laboratory experiments.

Point measurements at the three different areas were performed for all the experiments, with both diameters, 0.15 and 0.38 mm. The same temperature distribution was measured, independent of the diameter. Fig. 4.12 shows the temperature distribution for several temperatures for both of the wire dimensions tested in the laboratory experiments. As seen, the temperature range decreases with the decreasing temperature when forced air flow is applied on the simulated arc. The results prove that the temperature distribution is independent of the diameter of the wire.

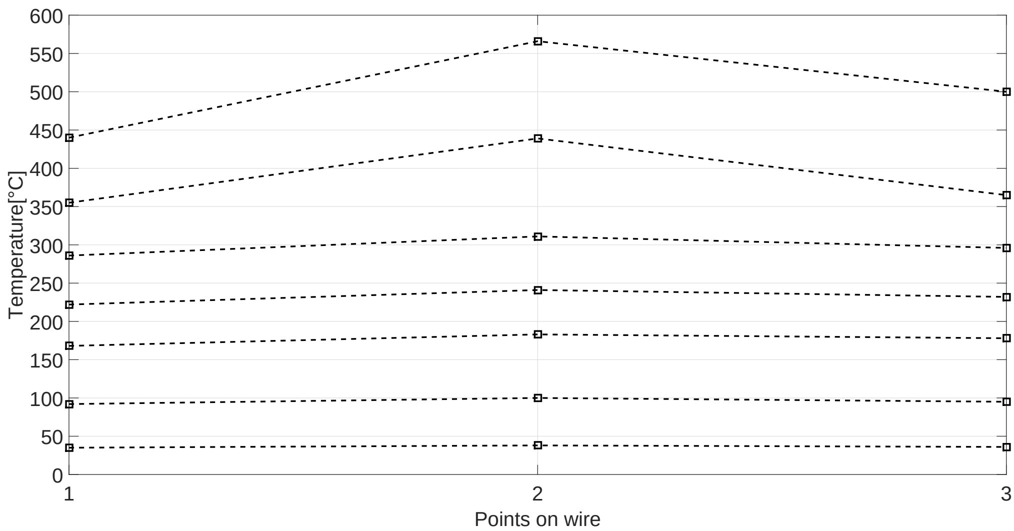


Figure 4.12: Heat distribution over simulated arc at different temperatures.

The temperature distribution is a result of two different effects going on in the process:

- Heat sinking of the connection ends
- Temperature coefficient,α, of the wolfram wire

According to the first law of thermodynamics, the heat flows from hotter objects to cooler ones. This results in a small temperature gradient across the wire. More power means higher temperature in the middle of the wire, than in the ends. A positive feedback effect is then obtained. Since the middle of the wire is hotter, this part will have a higher resistance, thus more power is dissipated. This continues until almost all the power is dissipated in the middle of the wire. Eventually, an equilibrium is reached where the thermal conductivity spreads the energy enough to balance the positive feedback effect.

4.5 Convection loss

Calculations of the convection loss were done using Eq. (3.9) with the measurements from Chap. 4.4. As mentioned, the laboratory results proved that the temperature distribution over the wire decreased with decreasing temperature. Thus, the convection loss should increase for each step with air flow applied onto to the simulated arc. Calculations for the convection loss for both wire diameters were performed.

Fig. 4.13 presents the axial and radial flow with the wolfram wire with a diameter of 0.15 mm. When no air flow was applied to the simulated arc, a convection loss of 0.0493 W was calculated. Some convection loss occurs even without any forced air flow, due to free convection, as explained in Chap. 2.5.3. The radial flow had a higher increase of the convection loss as a result of the more effective cooling. At 22.6 ln/min, a convection loss of 0.4825 W was calculated for the radial flow, compared to only 0.1790 W for the for the axial flow. The radial flow effectively cooled down the simulated arc with an air flow of 159 ln/min and reached its maximum convection loss, 1.15 W. The maximum value was reached at 249 ln/min for the axial flow.

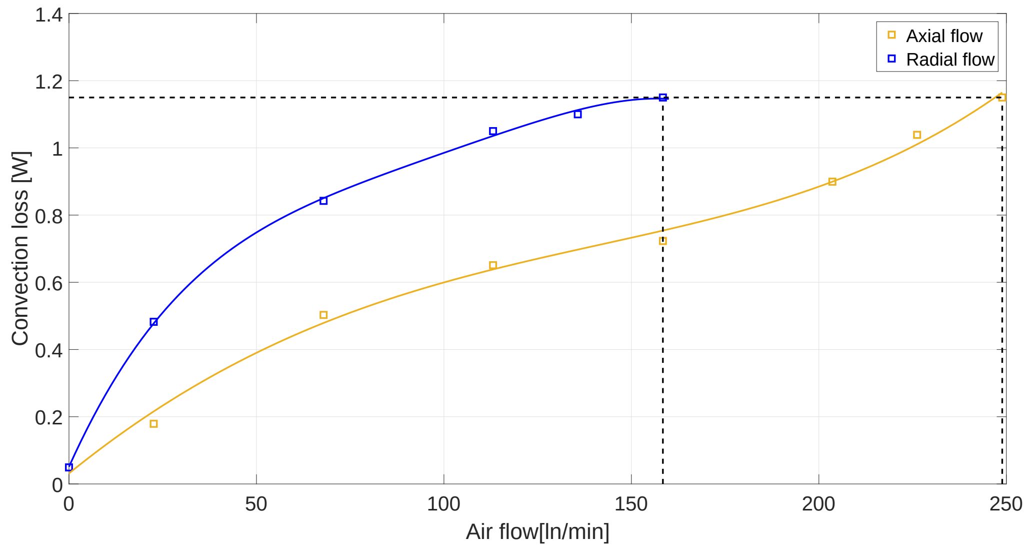


Figure 4.13: Convection loss for the wolfram wire with a diameter of 0.15 mm.

Fig. 4.14 shows the convection loss for the wolfram wire with a diameter of 0.38 mm. Because the wire had a larger surface area, a higher current was needed to heat up the simulated arc to the desired temperature. Hence, a higher convection loss is obtained. A convection loss of 0.2226 W was calculated without any forced flow, due to free convection. With 22.6 ln/min, the radial flow achieved a convection loss of 0.7029 W, while 0.4264 W was calculated for the axial flow. The radial flow quenched the simulated arc with an air flow of 159 ln/min and reached its maximum with a convection loss of 2.5 W. The maximum value was reached at 249 ln/min for the axial flow.

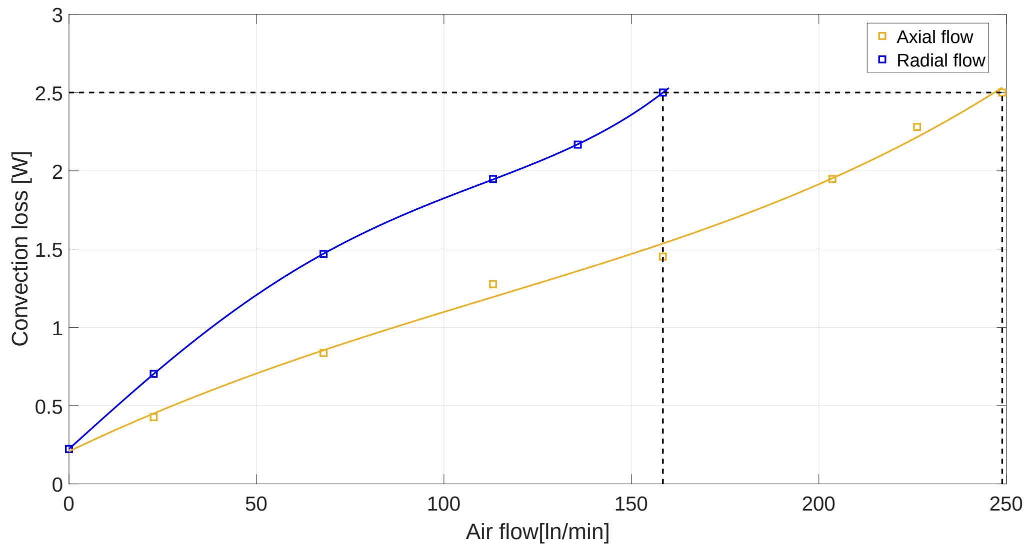


Figure 4.14: Convection loss for the wolfram wire with a diameter of 0.38 mm.

As seen in Figs. 4.13 and 4.14, the convection loss follows almost the same pattern for the two diameters. The increase of the convection loss with higher air flow/lower temperature is a result of the thermal radiation. When no air flow is applied, the temperature distribution has the highest difference. Hence, the thermal radiation is at its highest. Further, the thermal radiation will decrease with the temperature and the convection loss increase.

As mentioned in Chap 3.3, an approach to control the validation of the model is to check if the convection loss is independent of the wire diameter. Due to a larger surface area of the wolfram wire with a diameter of 0.38 mm, a higher current is needed to heat up the wire to the desired temperature. Accordingly, a higher convection loss is obtained. Hence, for the convection loss to be independent of the wire diameter, the convection per square millimeter of the surface area should be equal for the two wires. Fig 4.15 shows the calculations of convection loss per square millimeter for both wolfram wires with the axial and radial flow. As seen, some difference is seen. During the cooling process, not the total surface area is included during the air flow cooling. Accordingly, the air flow is not homogeneously divided, which creates some differences. Also, deviations during laboratory measurements must be considered when evaluating results. These factors can be seen as sources of error, which affects the results. Thus, considering these factors, it is assumed that the convection loss is independent of the wire diameter.

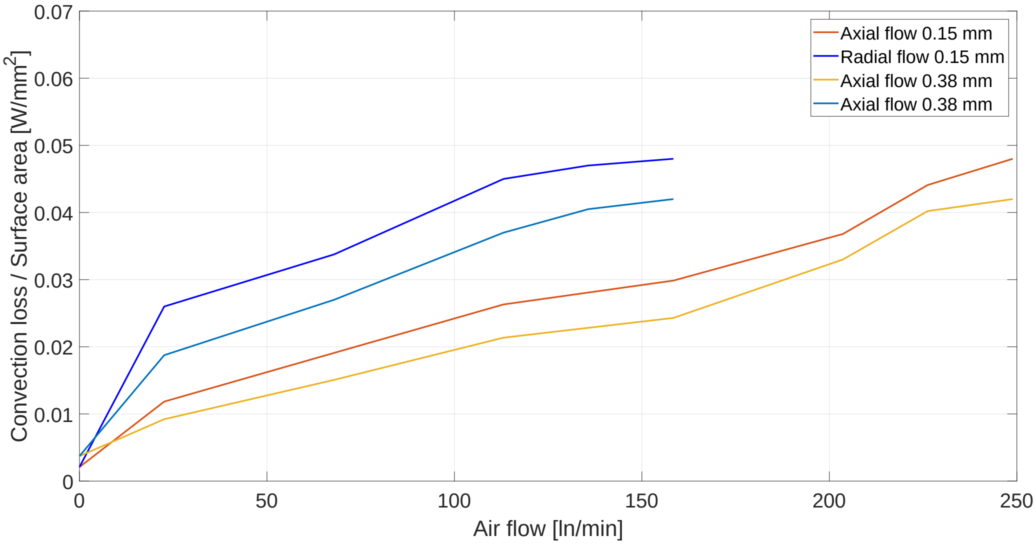


Figure 4.15: Convection loss per square millimeter for both the wolfram wires with diameters of 0.15 and 0.38 mm, applying axial and radial flow.

Chapter 5

FEM design

This chapter will describe how the simulated arc is built and tested by the use of an FEM-software. COMSOL Multiphysics™ is a powerful FEM-based modeling software capable of calculating multiple physical properties. In this thesis, COMSOL is used to calculate the temperature and heat distribution over the electrically heated wolfram wire simulating the arc.

5.1 Geometry

By making a COMSOL model, it was possible to look deeper into the heat distribution over the simulated arc, as well as comparing with the results obtained in the laboratory experiments. Fig. 5.1 shows a part of the geometry built in COMSOL. *2D axissymmetric* was used as space dimension. This made it possible to only build a quarter of the total design, which also decreased the solver time. Wolfram was selected as the material in the inner rectangle, working as the wolfram wire in the laboratory setup. Air was selected in the outer rectangle, operating as the surrounding temperature of 20°C. *Joule Heating* was used with *Electric Currents* and *Heat Transfer in Solids* as the physics. By using these applications it was possible to heat up a wolfram wire by applying a current and taking the heat transfer modes: conduction, radiation and convection into consideration.

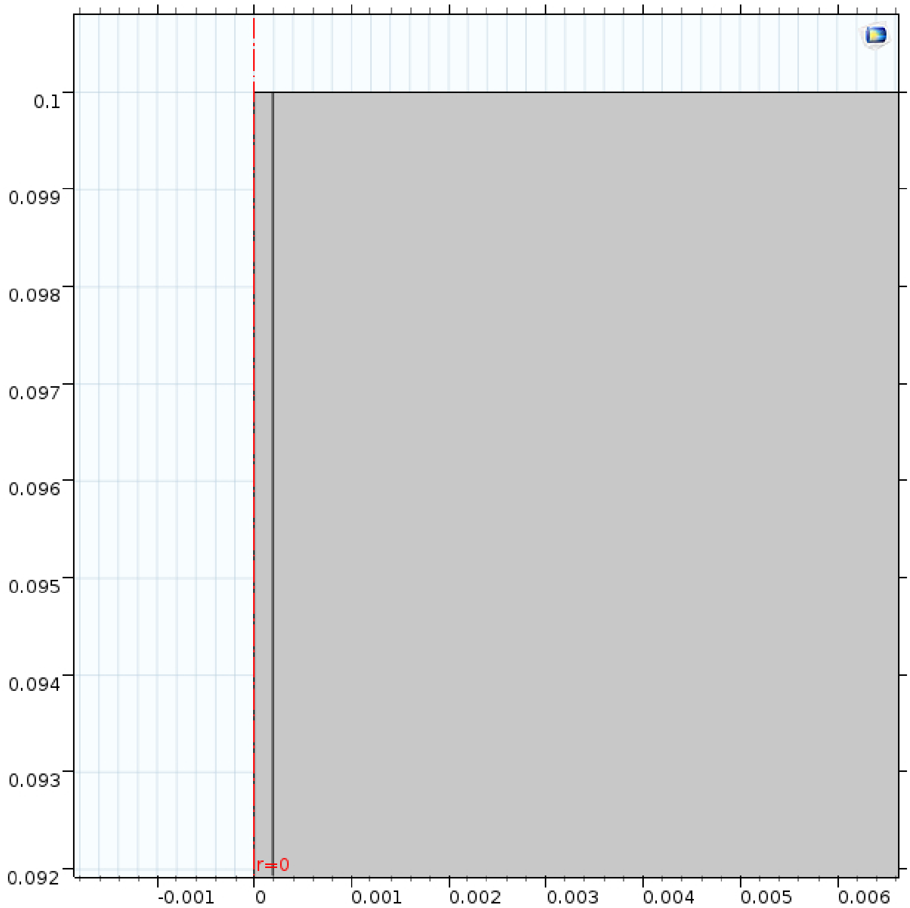


Figure 5.1: The 2D axissymmetric geometry for the simulation model created in COMSOL Multiphysics.

When applying air flow on the simulated arc, the physics *Laminar flow* and *Turbulent flow* were used for the axial and radial flow respectively. Laminar flow turned out to be a good comparison of the axial flow, with the same air flow pattern straight over the heated wire. Making the radial flow in COMSOL turned out to be more challenging. Hence, using turbulent flow was used. Therefore, more exact simulations for the axial flow compared to the radial flow were obtained.

COMSOL only express air flow in velocity [m/s] and pressure [Pa]. Therefore, conversion of the air flow expressed in the air flow generator [ln/min], to either air pressure [Pa] or air velocity [m/s] was needed. Converting to air velocity was chosen due to the calculation procedure and relevance for comparison.

In the simulation model, the cooling process starts at the end of the air cable compared to the laboratory setup. Eq. (5.1) expresses the process in the laboratory setup, where A is the cross section of the air tube where the air flow is blown from, and v the velocity of the air flow.

$$Avdt = dV \tag{5.1}$$

In Eq. (5.2), the expression is altered to get $\frac{dV}{dt}$ alone. This expresses the air flow from the generator, in ln/min.

$$\frac{dV}{dt} = Av \tag{5.2}$$

Eq. (5.3) is the final expression of the converting from air flow expressed in ln/min to air velocity in m/s. At last, the air flow expressed in ln/min is expressed in SI units to get the air velocity in the right unit, m/s.

$$v = \frac{1}{A}\frac{dV}{dt} \tag{5.3}$$

By using Eq. (5.3) one can use the same air flow used in the laboratory, only expressed in m/s in COMSOL.

5.2 Mesh

In FEM tools, the mesh is a grid which is distributed across the volumes and surfaces of each model part. The intersections in the mesh define a coordinate in which a value should be calculated. Mesh sizing is a trade-off between accuracy and simulation time, but can be adjusted with different sizes for various parts. To get results as accurate as possible, it is important to have a good mesh. By making a custom made mesh it is possible to get more accurate calculations in the areas we want to look deeper into. Since the heat distribution in the wolfram wire is the most interesting, the mesh around it is extremely fine. The accuracy decreases further away, as shown in Fig. 5.2.

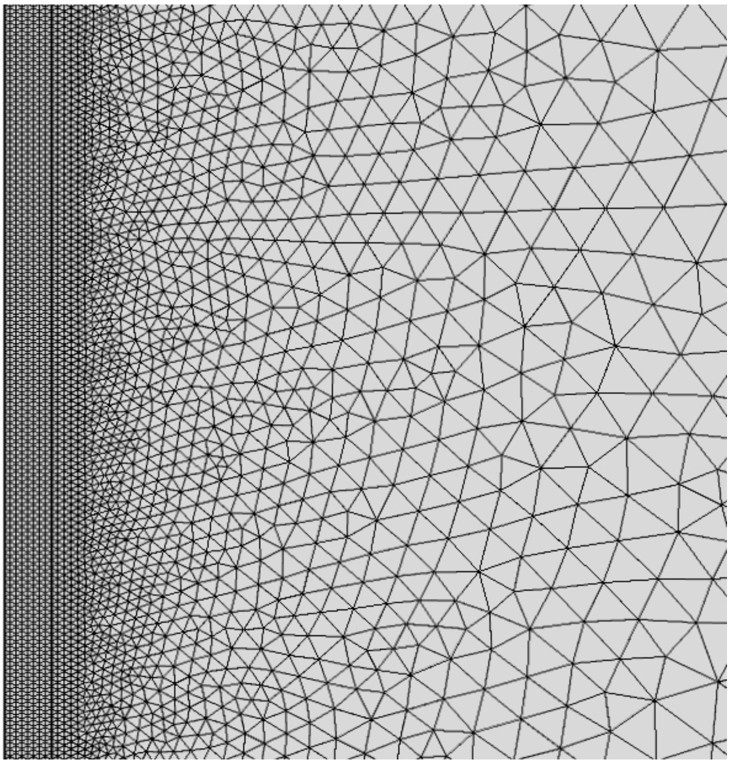


Figure 5.2: Mesh for the COMSOL model.

5.3 Parameters

Table 5.1 shows the parameters set in the COMSOL model.

Table 5.1: Model parameters for COMSOL model.

Name	Expression	Description
l	50 [mm]	Length of wire
d	0.15,0.25,0.38 [mm]	Diameters of wire
I	0-10 [A]	Injected current
U	0-3 [V]	Measured voltage over wire
v	0-100 [m/s]	Forced air flow on the wire
A_{cs}	$\pi\left(\frac{d}{2}\right)^2$ $[m^2]$	Cross-section of wire
A_s	$\pi d l$ $[m^2]$	Surface area of wire
J	$\frac{I}{A_s}$ [V]	Current density

Chapter 6

Simulation results

In this chapter, the simulation results performed in COMSOL 5.2a are conducted. This gives a good comparison to the laboratory results, including heat distribution and the cooling process of the simulated arc.

6.1 Temperature distribution without air flow

By making a model of the simulated arc in COMSOL Multiphysics, the temperature distribution over the arc was found. As mentioned in Chap 5.1, the physics used was: *Joule Heating* with *Electric Currents* and *Heat Transfer in Solids* when no air flow was implemented in the model. Fig. 6.1 presents the temperature distribution over the simulated arc, created similarly as in the laboratory experiments, with a 5 cm long wolfram wire having a diameter of 0.38 mm and 10 A applied through the wire. Simulation with a diameter of 0.15 mm was also done. The same temperature was then obtained, giving the same heat distribution independent of the wire dimension.

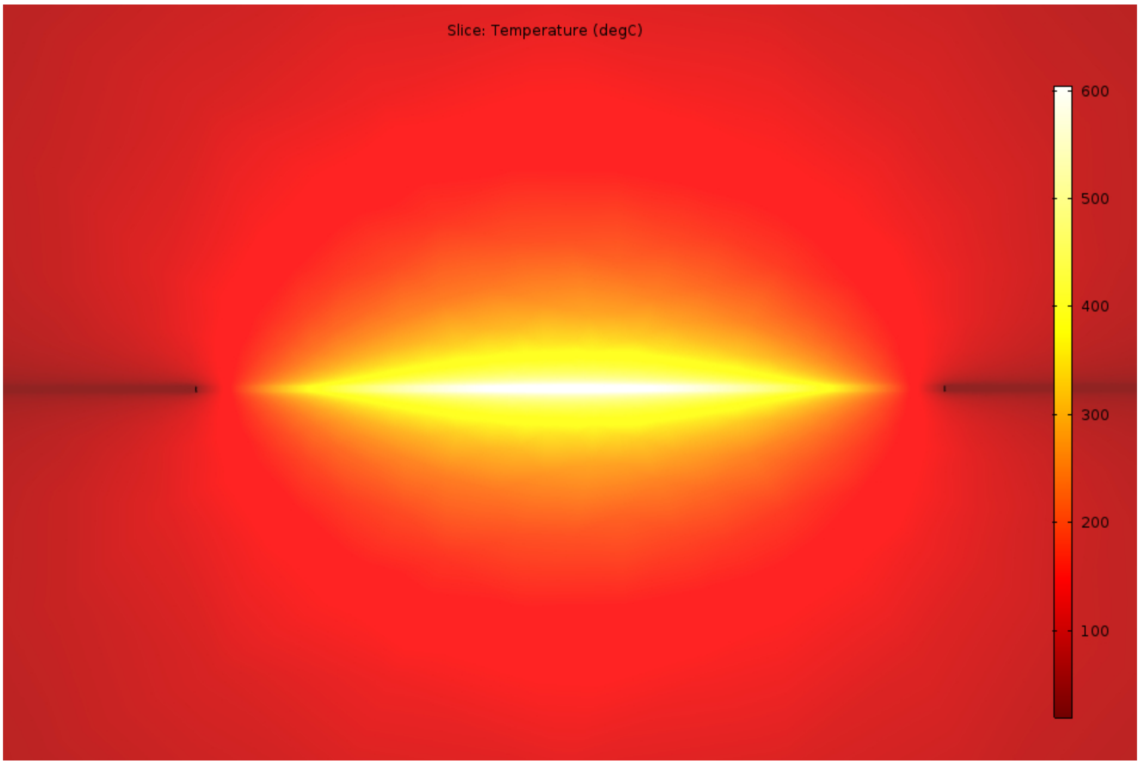


Figure 6.1: Heat distribution over wolfram wire with a diameter of 0.38 mm, simulated in COMSOL.

As seen from Fig. 6.1, the simulated arc distributed the most heat in the middle area, with a temperature decrease towards the ends. In the middle area, a temperature of 605°C was reached, while towards the ends, a temperature of 495°C was reached.

Fig. 6.2 illustrates the distributed heat over the wire without the heat dissipation. This corresponds to Fig. 6.1, with decreasing temperature towards the ends. This is also illustrated in Fig. 6.3 where the temperature contour is shown.

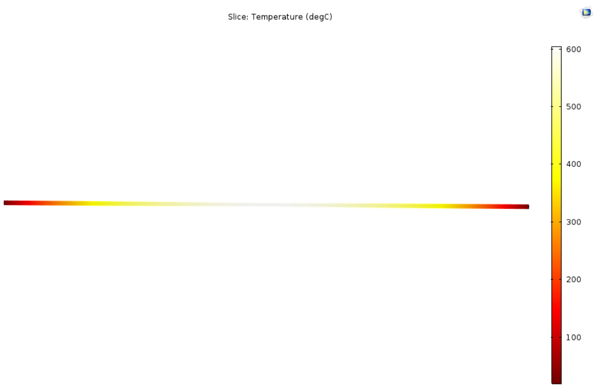


Figure 6.2: Heat distribution over the wire.

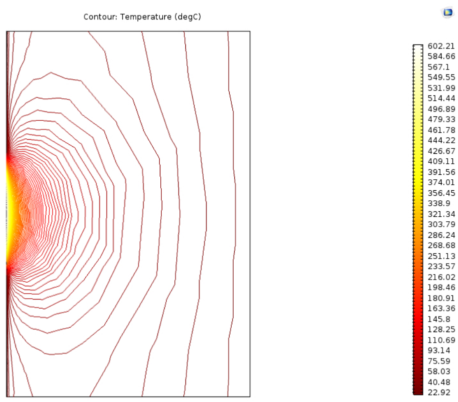


Figure 6.3: Isothermal contours for the simulated arc.

By making a dataset of the temperature in Fig. 6.2, the heat distribution is shown in Fig. 6.4. As seen, the temperature vary from approximately 605°C at the most heated areas in the middle area, to 495°C in the ends. This gives a temperature difference of approximately 110°C without any forced flow on the simulated arc. This corresponds to the laboratory results in Chap 4.4.

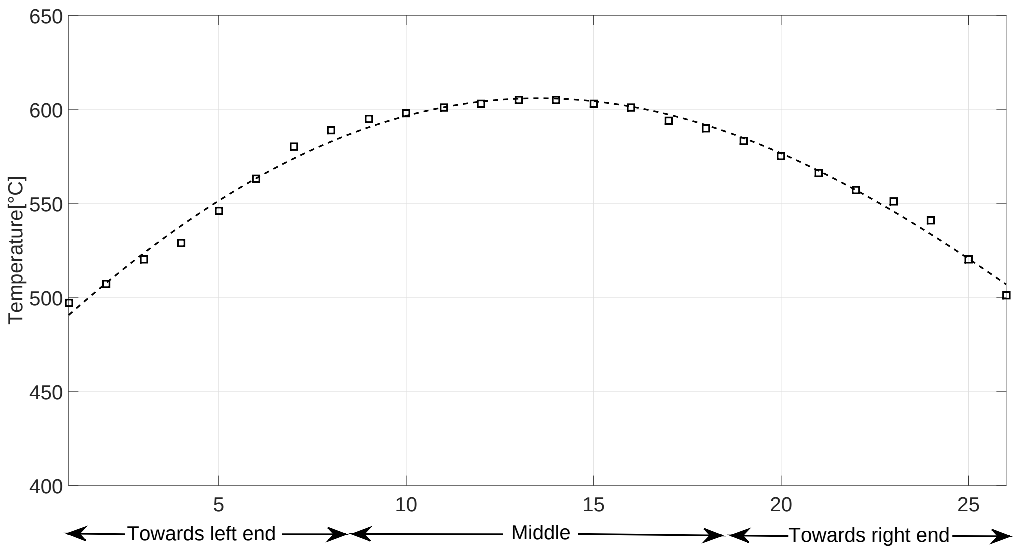


Figure 6.4: Heat distribution over wolfram wire with a diameter of 0.38 mm.

The model distributed more heat compared with the laboratory results. With the same parameters, approximately 40°C more were obtained. A difference of 40°C is natural when considering external influences that are difficult to take into account with the simulations. It was decided that the model gave a good comparison to the laboratory experiments and further simulations were done.

6.2 Laminar flow

Next, applying air flow into the simulated arc was completed. As mentioned in Chap. 5.1, the physics *Laminar flow* was needed. The same air flow was used in the simulations as in the laboratory, thus ln/min was converted to m/s, using Eq. (5.3). Table 6.1 shows the relevant values used as the basis for the simulations.

Table 6.1: Air flow parameters for the axial design.

Air flow [ln/min]	Velocity [m/s]
0	0
22.6	9.46
67.9	28.42
113.1	47.34
158.4	66.31
203.6	85.23
226.2	94.68
248.9	114.19

For simulations with laminar flow, Fig. 6.1 represented the starting conditions when no forced air flow was applied. Hence, a temperature of 605°C in steady state at the hottest area of the arc. From the calculations, 22.6 ln/min equaled to a velocity of 9.46 m/s. This resulted in a decrease of the temperature over the simulated arc to 324°C. See Fig. 6.5. As seen, the heat kept its maximum towards the center, however against a larger area toward the connection end, furthest away from the nozzle area.

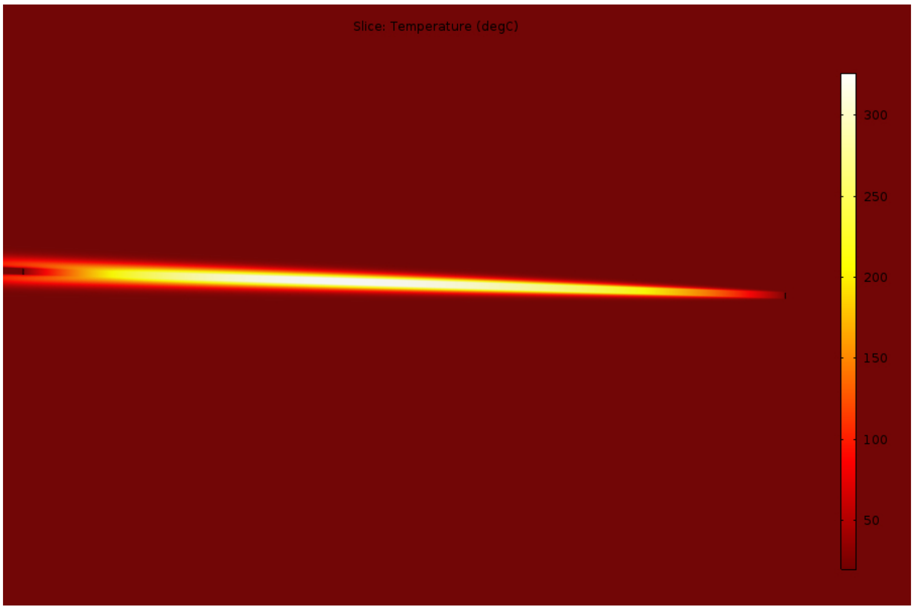
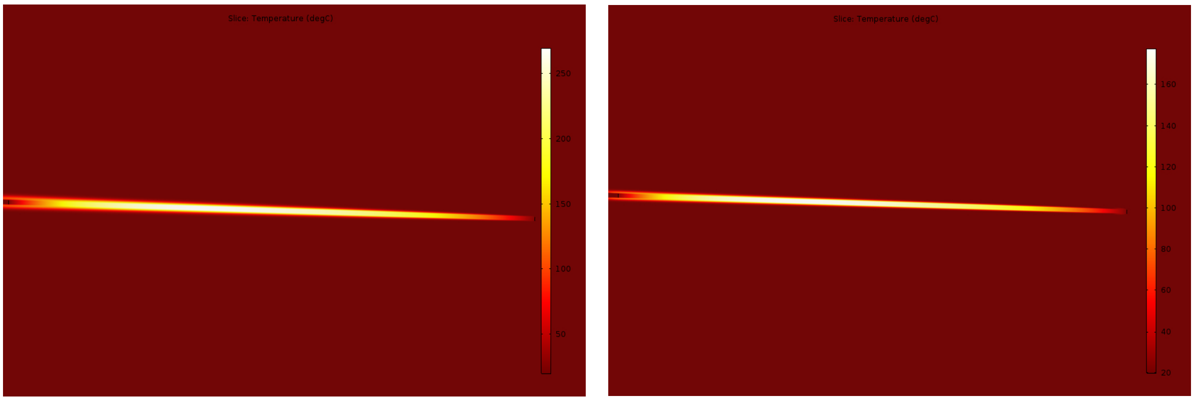


Figure 6.5: Temperature distribution over the simulated arc with an air flow velocity of 9.46 m/s.

As with the laboratory experiments, a slower cooling appeared with the increased steps of applied air flow. With an air velocity of 28.42 m/s, the simulated arc temperature was decreased to 264°C. Further increase of the air velocity, to 66.31 m/s, a temperature of 178°C was reached. With a velocity of 85.23 m/s the simulated arc temperature was decreased to 89.2°C. Fig. 6.6 shows the temperature over the wire with an air velocity of 28.42 m/s and 66.31 m/s.



(a) (b)

Figure 6.6: Temperature cooling using air velocities of (a), 28.42 m/s, and (b), 66.31 m/s, with laminar flow.

With an air flow velocity 97 m/s, the simulated arc was successfully quenched and obtained a temperature equal to the ambient temperature, as seen in Fig. 6.7. This means that the simulation model needed approximately 10 ln/min less air flow than the laboratory model to quench the simulated arc.

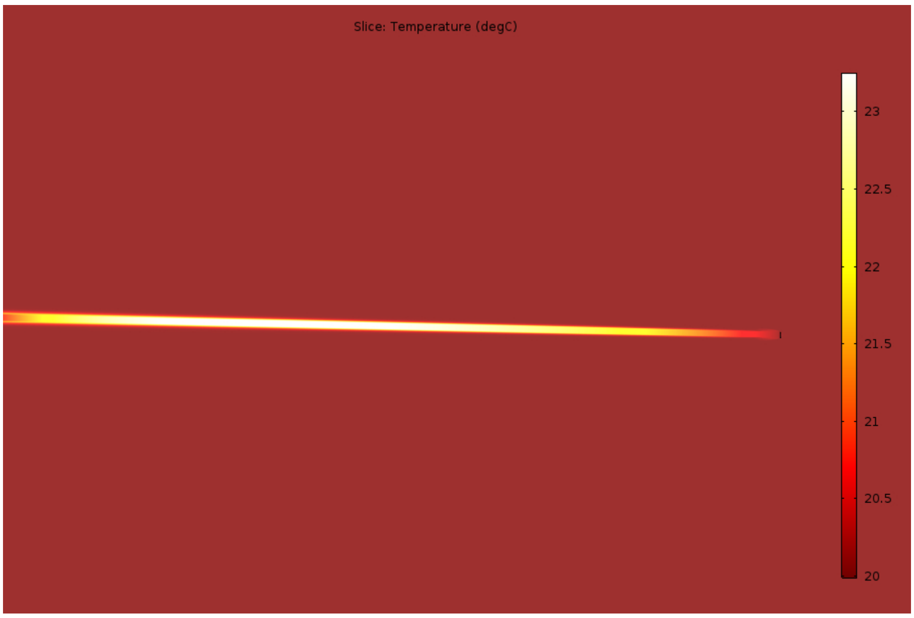


Figure 6.7: Temperature distribution over the simulated arc with an air flow velocity of 94.68 m/s.

Fig. 6.8 presents the simulation results of the temperature cooling with laminar flow. As seen, a high temperature drop occurred up to 20 m/s. From 20 m/s to 60 m/s, the temperature stabilized better. From 60 m/s to 97 m/s a stable decrease of the temperature took place and ultimately got the simulated arc down to the ambient temperature. A similar air flow and cooling pattern were obtained between the axial design and the simulation model with laminar flow. Thus, the model proved to be a good comparison of the axial design.

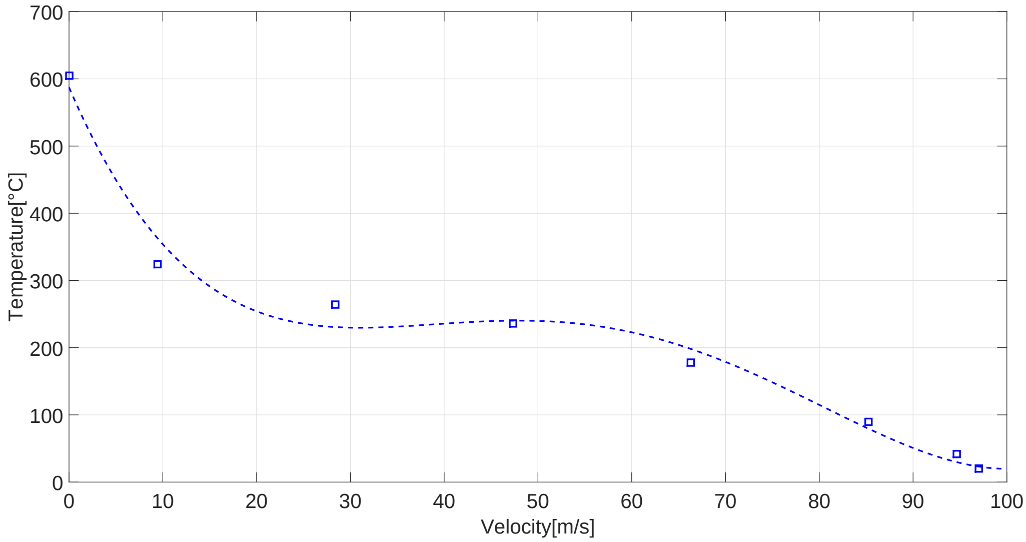


Figure 6.8: Cooling of the simulated arc with the simulated axial flow.

6.3 Turbulent flow

When simulating the radial flow in COMSOL, the *Turbulent Flow* physics was used. Turbulent flow compared to the radial flow did not give the same exact comparison of the air flow pattern. Creating the radial flow in COMSOL turned out to be difficult. Hence, the turbulent flow was used. Using turbulent flow also helps give an idea about how much turbulent flow is formed with the radial design in the laboratory. Table 6.2 displays the different air flows tested in the radial flow experiments and the air velocities converted to the simulations used in COMSOL. As with laminar flow, increased steps of forced air flow were performed.

Table 6.2: Air flow parameters for the radial design.

Air flow $[ln/min]$	Velocity $[m/s]$
0	0
22.6	9.46
67.9	28.42
113.1	47.34
135.7	56.80
158.4	66.31

As with the laminar flow, Fig. 6.1 operated as the starting condition before applying turbulent flow in the simulations. Firstly, an air velocity of 9.46 m/s was applied onto the simulated arc. See Fig. 6.9. This decreased the temperature down to almost half, 307°C, resulting in a temperature drop of 298°C.

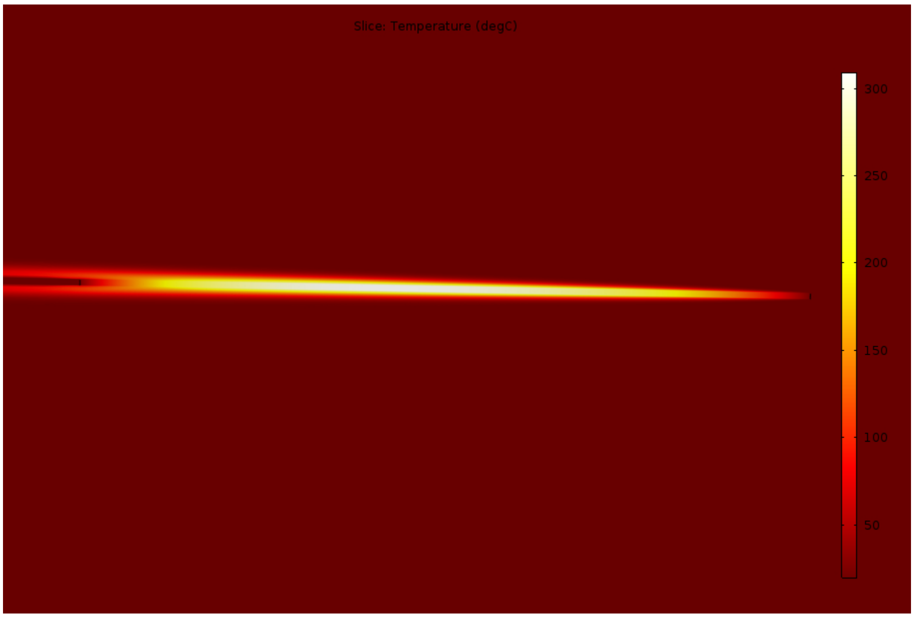
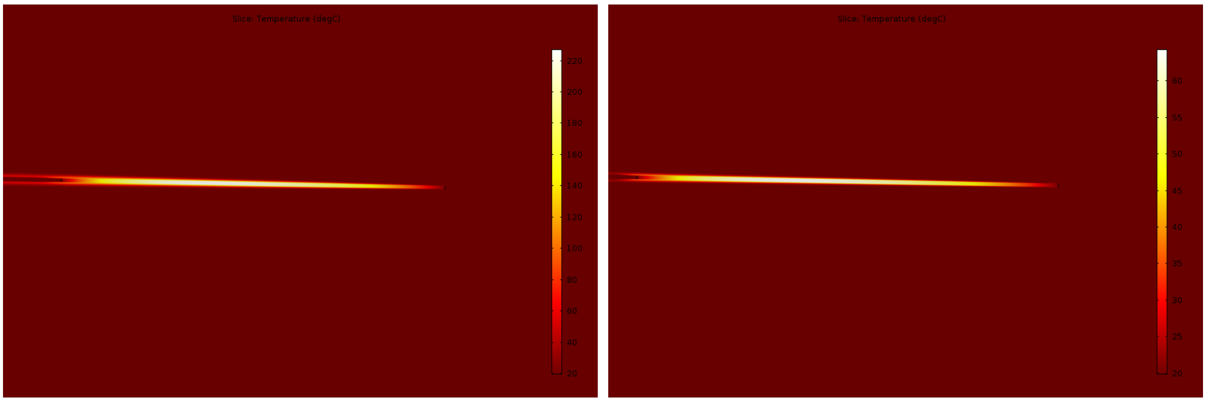


Figure 6.9: Temperature distribution over the simulated arc with an air flow velocity of 9.46 m/s.

Next, higher air velocities were tested. Fig. 6.10 shows the simulation results with air velocities of (a), 28.42 m/s and (b), 56.8 m/s. With 28.42 m/s the temperature decreased down to 227°C. Next, with 47.34 m/s, the simulated arc was cooled down to 138°C. By applying 56.8 m/s the simulated arc was almost successfully cooled down, to a temperature of 64°C.



(a) (b)

Figure 6.10: Temperature cooling with use of turbulent flow. In (a) an air velocity of 28.42 m/s and (b), an air velocity of 56.8 m/s is tested.

The simulated arc was successfully quenched with an air velocity of 60 m/s using turbulent air flow. Fig. 6.11 shows the heat distribution where the temperatures vary from 24-20°C.

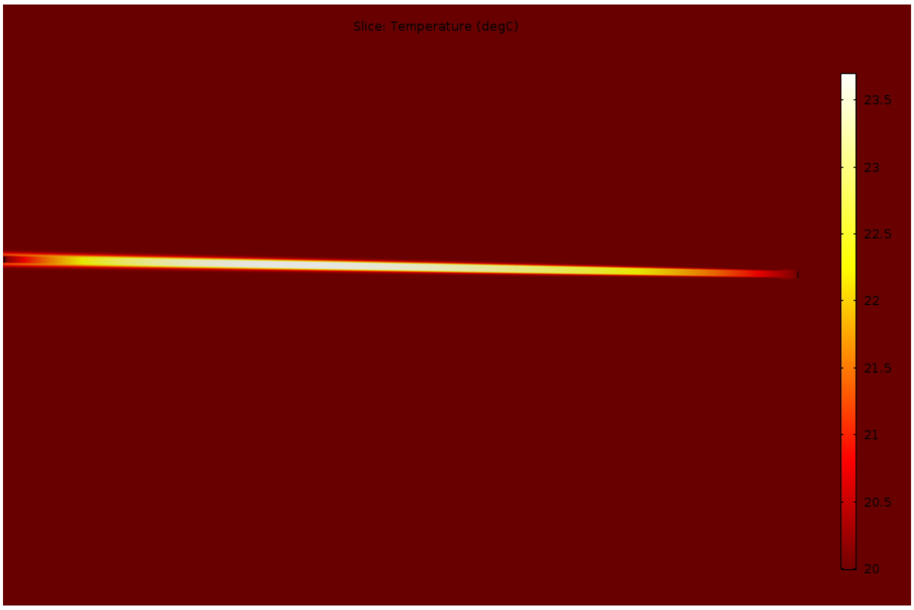


Figure 6.11: Temperature distribution over the simulated arc with an air flow velocity of 62 m/s.

Fig. 6.12 shows the temperature cooling with the turbulent flow. As shown, the temperature almost halved with only 9.46 m/s. From 20 m/s to 40 m/s the cooling stabilized more, as with laminar flow. Further, the cooling almost fell linearly down until the simulated arc was quenched at 60 m/s.

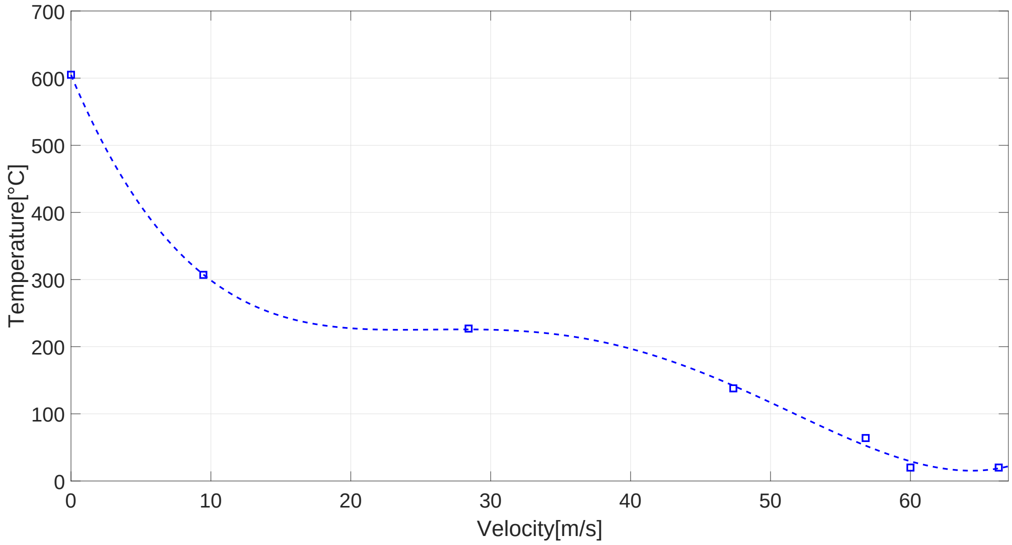


Figure 6.12: Cooling of the simulated arc with the turbulent flow.

The results show that the turbulent flow was approximately 38% more effective than the laminar flow, under the same parameters. The results also prove that the air velocity needed to quench the simulated arc at a temperature of 605°C is well below the supersonic level, 343 m/s. A good simulation model of the radial designed was not obtained. The same air flow pattern turned out to be difficult, and the model does not create the same air flow pattern as the radial flow used during the laboratory experiments.

It is also important to point out that the converting calculations from the laboratory experiments to the simulation is not exact. In the laboratory experiments, the air flow is affected by the edges of the nozzle and the wolfram wire. This is not taken into consideration in the simulation. Hence, the air flow in the laboratory experiments is somewhat reduced. This is neglected when doing the calculations for the simulation.

Chapter 7

Discussion

7.1 Laboratory results

7.1.1 Air flow designs

The laboratory experiments showed that the temperature cooling was independent on the two wire diameters, 0.15 and 0.38 mm. Some change in value was measured between the diameters, but in the end, the same amount of air flow was needed to successfully cool down the heated wire. Larger differences in the diameter could have an impact on the cooling. However, the results show that the dependent factor in the performed laboratory experiments was the temperature applied over the simulated arc.

With the axial design, an air flow of 249 ln/min was needed to quench the simulated arc given a starting temperature of 570°C. This concerned all the five placements tested, as seen in Fig. 3.1. Some variation of the temperature cooling was measured for the different locations, but the same amount of air flow was needed to cool down the heated wire to the ambient temperature during all the experiments. Accordingly, the results show that the axial flow has a constant air flow through the nozzle, and thus the cooling is independent of the placement.

With the radial flow, an air flow of 159 ln/min was needed to quench the arc given a starting temperature of 570°C. This concerned only the middle placement of the wire. At the other locations, the radial flow did not provide the same cooling efficiency. Here, approximately 15-20 ln/min more were needed to quench the simulated arc. This indicates that the radial flow creates a higher velocity of the air molecules towards the middle of the nozzle. Hence, giving an optimal cooling when the arc is in the center of the nozzle.

With a starting temperature of 570°C over the simulated arc, the radial design turned out to be approximately 35 % more efficient than the axial design. Measurements with other starting temperatures (see appendix B for more laboratory results), seemed to indicate that the radial/axial flow difference increased at higher temperatures. This proves the importance of the angle when blowing air flow on an arc. Some assumptions of why the radial flow gave a more efficient cooling than the axial flow is:

- Grater share of the air flow contributing.
- Turbulent flow.
- Stagnation point.

The results indicate that a greater share of air flow is contributed close to the simulated arc. With the axial design, the air flow is blown straight onto the wire. The air flow will then naturally follow a pattern where the air flow in the center increases compared to in the edges. With the radial design, the air flow is blown onto the wire, which indicates a higher contribution over the simulated arc.

The radial design results also indicate that a good mixture is created, which leads to some creation of turbulent flow. This is proved to improve the interrupting capability.

Another assumption is that a stagnation point is created. The wire can be seen as a stagnation point where air flow flies along a streamline straight on the wire. The air molecules will then slow down on the way. Since the air flow cannot pass through the wire, high pressure is made, and gives an acceleration of the air molecules alongside the wire. Consequently, they will travel faster, with more molecules contributing in the process, making the cooling more effective. This is not always valid and is geometry dependent. It is therefore only an assumption.

7.1.2 Heat distribution

The point measurements contributed to give a good picture of the heat distribution over the wire. As in a high pressure arc, the temperature was highest in the middle. Also, as assumed, the temperature difference over the wire decreased with increased air flow and thus decreased temperature. The simulated arc emitted the most radiation when no forced air flow was applied, which means when the temperature difference was at its highest. The more air flow applied onto the arc, the lower the temperature difference. Accordingly, the emitted radiation decreased with the increased air flow. The same relationship concerned the heat conduction. The higher the temperature, the more heat conduction over the simulated arc. For the experiments in this thesis, the heat conductance did not reach high values and did not influence the convection loss much.

The convection loss showed that the radial flow had a steeper increase and more effective cooling. See Fig. 7.1. Some convection loss occurred when no forced flow was applied, due to free convection. The increase of the convection loss is a result of the decreasing radiation. The results show that how much heat transferred by convection is dependent on how large the rate of air flow is and the angle applied.

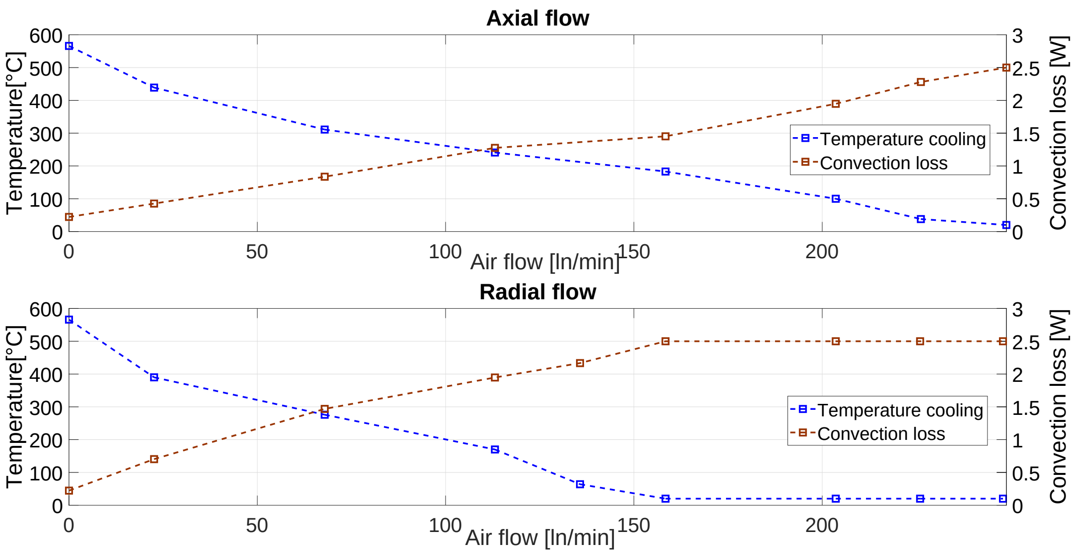


Figure 7.1: Temperature cooling and convection loss for the axial- and radial flow with a 10 A current applied over a wolfram wire with a diameter of 0.38 mm.

Due to a larger surface area over the wolfram wire with a diameter of 0.38 mm, a higher current was needed to heat up the wire to the desired temperature. Accordingly, a higher convection loss was obtained. Therefore, to check the validation of the model, P_{conv}/A_s was calculated for both wire diameters and air flow designs. As shown in Fig. 4.15, some difference occurred for the two diameters. During the cooling process, not the total surface area was included during the air flow cooling. Hence, the air flow is not homogeneously divided, which creates some differences. Also, deviations during laboratory measurements must be considered when evaluating results. These factors can be seen as sources of error, which affects the results. Thus, considering these factors, it is assumed that the convection loss is independent of the wire diameter. Accordingly, convection can describe the efficiency of the cooling: high increase of convection indicates a more effective cooling, and a more effective cooling results in less probability for thermal and dielectric re-ignitions. This means that the switch can interrupt higher currents.

7.2 Simulation results

The FEM-model made in COMSOL proved to be a good comparison for the laboratory experiments. The heat distribution had a very similar pattern to the point measurements, with the use of the same parameters. As in a high pressure arc, the temperature was highest in the middle. The model gave a much more detailed distribution, which gave the opportunity to look more into the simulating arc, as seen in Fig. 6.4. By simulating the different diameters of the wire, 0.15 and 0.38 mm, the temperature over the arc proved to be the dependent factor for the heat distribution. For further simulations, only the 0.38 mm wolfram wire was used, with a 10 A current applied. This gave a temperature of 605°C in the middle of the simulated arc, and 495°C in the ends. That means around 35°C more than measured in the lab.

Simulations of the axial flow were performed using the laminar flow physics in COMSOL. The air flow was blown straight on the heated wire, as with the axial design. The simulation model turned out to be a good comparison for the axial design, and similar results were obtained. When performing the air flow cooling, an air flow velocity of 97 m/s was needed to quench the simulated arc. This means, approximately 232 ln/min, compared to 250 ln/min in the laboratory experiments.

When simulating the radial design, creating the same air flow pattern turned out to be difficult. Hence, the turbulent flow physics in COMSOL was used. With the turbulent flow, an air velocity of 60 m/s was needed to quench the simulated arc, i.e. approximately 143 ln/min, compared to 160 ln/min in the laboratory experiments. Even though a different air flow pattern was performed, some similarities of the cooling process with the radial flow were obtained. Hence, the simulation results indicate that some turbulent flow is created by the radial design. If this is the case, this contributes to a more efficient cooling process.

For both cases, a more efficient cooling was obtained compared to in the laboratory experiments, even do a higher starting temperature was obtained over the heated wire. The turbulent flow turned out to be approximately 38 % more efficient than the laminar flow. This is a little more than in the laboratory results. Fig 7.2 displays a comparison between the results obtained in the laboratory experiments and the simulations. As seen, the axial and laminar flow had a more similar pattern compared to the radial and turbulent flow. This was expected, because of the more accurate simulation of the air flow design.

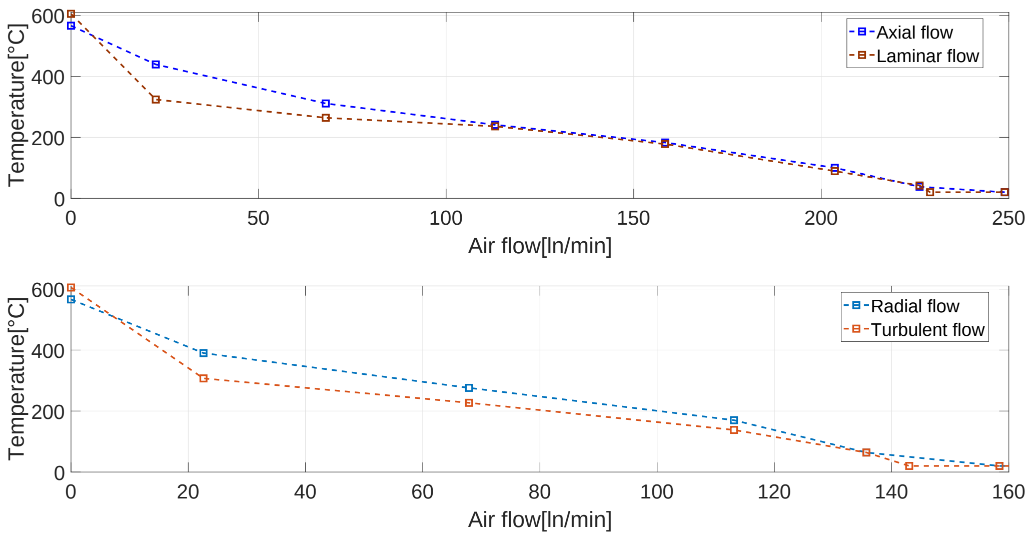


Figure 7.2: Laboratory results compared to the simulations results with 10 A applied over a wolfram wire with a diameter of 0.38 mm.

In the laboratory experiments, the air flow was affected by the edges of the nozzle and the wolfram wire. This is not taken into consideration with the simulations in COMSOL. Hence, the air flow in the laboratory experiments is somewhat reduced. This is neglected when doing the calculations for the simulation, together with other external factors that are difficult to obtain in simulations. In addition, deviations must be taken into account when doing laboratory measurements. These factors can be seen as sources of error, and thus explain some of the differences in the results.

Chapter 8

Conclusion and Further Work

8.1 Conclusion

By using a simplified experimental setup based on steady-state air flow and with an electrically heated wolfram wire, cooling of a simulated arc was done. By testing different diameters of the wolfram wire, 0.15 and 0.38 mm, it was found that the temperature cooling was independent on the wire diameters. Laboratory experiments with different wire locations showed that the axial flow had a constant air flow through the nozzle, and thus the cooling is independent of the placement. In contrast, a more efficient cooling was obtained with the wire located in the middle, compared with the other placements, for the radial flow. Hence, a higher velocity of the air flow was created towards the center out from the nozzle. Therefore, with the use of the radial design, an optimal cooling is obtained when the arc is located in the center of the nozzle. With a starting temperature of 570°C over the simulated arc, the radial design turned out to be approximately 35 % more efficient than the axial design. The results indicate that the difference of the cooling increases with higher temperatures. Accordingly, the results show the importance of the angle when cooling an arc with air flow.

Calculations of the convection loss confirmed that the convection loss increases with stepwise air flow. Calculations of the convection loss per square millimeter over the wire indicate that the convection loss is independent of the wire diameter when neglecting possible deviations. Accordingly, the convection loss is dependent on the air flow, which verifies the validation of the model. Hence, the convection loss can describe the efficiency of the cooling:

high increase of convection indicates a more effective cooling and a more effective cooling result in less probability for thermal and dielectric re-ignitions. This means that the switch can interrupt higher currents.

The simulation model made in COMSOL turned out to be a good comparison to the laboratory experiments. A more detailed heat distribution was obtained over the simulated arc with the simulations, compared to the point measurement performed in the laboratory. The simulation model of the axial flow proved to be a good comparison. The same air flow pattern and an equal cooling process were obtained. Making a simulation model of the radial flow turned out to be more complex and a more inaccurate model was made. For the radial design, turbulent flow was used, and accordingly a different air flow pattern. However, some similar results were obtained, which indicates some creation of turbulent flow with the radial flow.

When evaluating the results, some considerations needs to be taken into account. In the laboratory experiments, the simulated arc was attached to a stable setup, while when cooling a plasma, the ionized air will move around when air flow is applied. With the axial flow, the arc would be pressed against the wall, which would influence the cooling. Hence, the radial design can be seen as more realistic, where air flow is blown around the arc. It is also important to acknowledge deviations when doing measurements in the laboratory. In addition, the connections ends and the nozzle may influence the temperature cooling. Considering the simulations results, influences of the edges from the nozzle and wolfram wire, together with external factors is not taken into account. This may be a factor for some of the difference in the results between the laboratory experiments and simulations results.

8.2 Recommendations for Further Work

Based on discussion, some important aspects for further work and evaluation are:

- Further work on the COMSOL model. A good comparison of the axial flow was obtained in the simulations, but the model for the radial flow did not work as good. Making a better simulation model of the radial flow could be interesting.
- Test more wire dimensions. For the laboratory experiments, wolfram wires with diam-

eters of 0.15 and 0.38 mm were tested. It could be interesting to test more diameters to check if the convection loss is independent of the wolfram wire for both thicker and thinner diameters.

- Try different nozzle designs. Different nozzle designs has not been tested in this master thesis. In order to achieve the correct and efficient air flow on the burning arc, the nozzle design is very important. Hence, this would be an interesting thing to investigate.
- Try a different measurement method. In the laboratory experiments, measurements of the voltage over the wire as done to find the temperature. This method gives some deviations. Using an infrared camera and a resistance wire could give more exact results in the laboratory experiments and would be interesting to try.
- Develop and test several air flow designs. In the master thesis two different air flow designs were made and tested. The radial design proved to be more efficient. Designing and testing more designs may provide an even better understanding for air as interruption medium.
- Electrical experiments in a high-voltage laboratory would be highly relevant. To see the difference between heating a wire and plasma, and get more realistic pictures of the effects.

Appendix A

Acronyms

MV Medium voltage

HV High voltage

LBS Load break switch

CB Circuit breaker

FEM Finite element method

Appendix B

Laboratory results

B.1 Air flow cooling

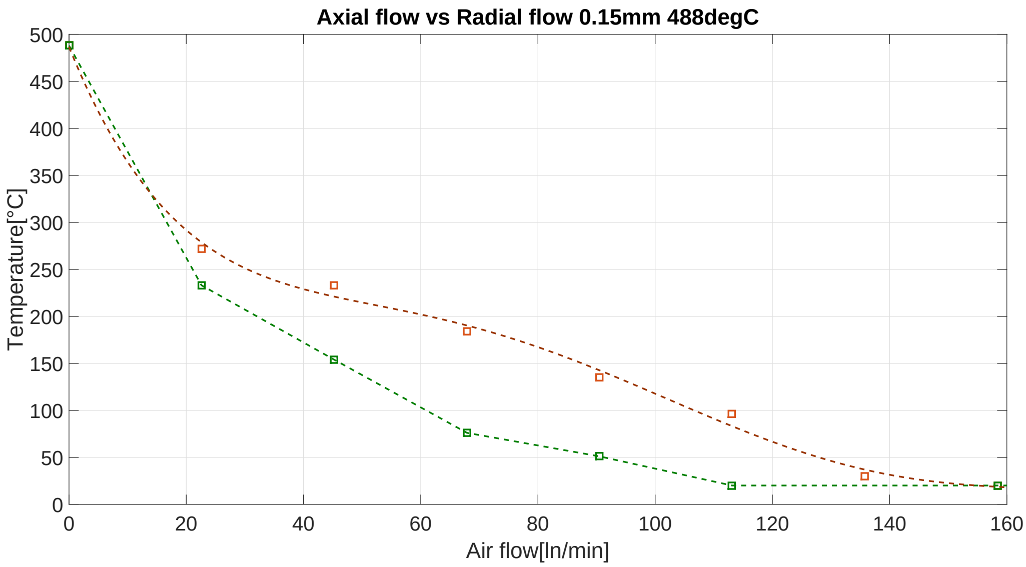


Figure B.1: Air flow cooling of the simulated arc with a starting temperature of 488°C. Wolfram wire with 0.15 mm.

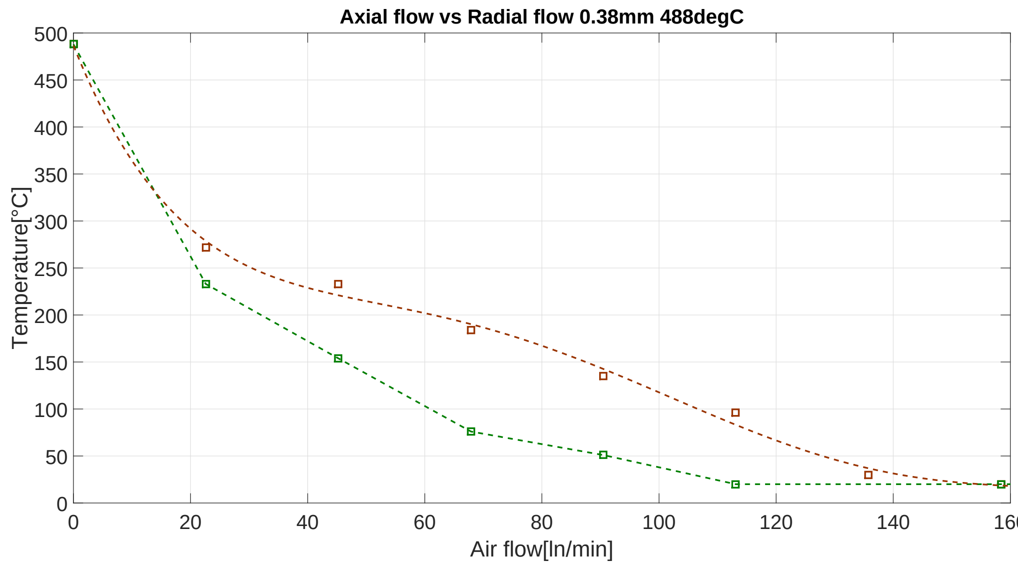


Figure B.2: Air flow cooling of the simulated arc with a starting temperature of 488°C. Wolfram wire with 0.38 mm.

B.2 Convection loss calculations

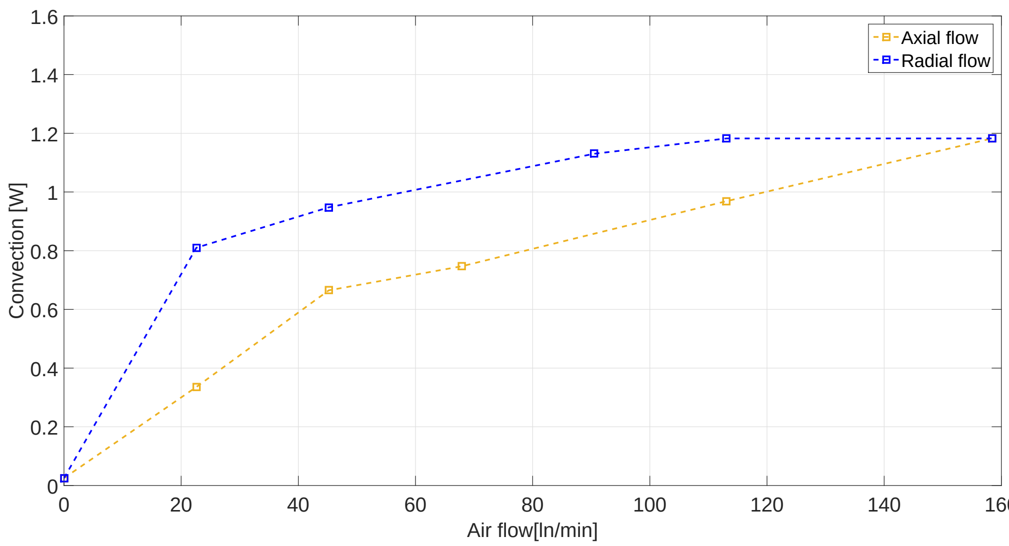


Figure B.3: Convection loss for axial and radial flow with a wolfram wire with diameter of 0.15 mm and a starting temperature of 488°C.

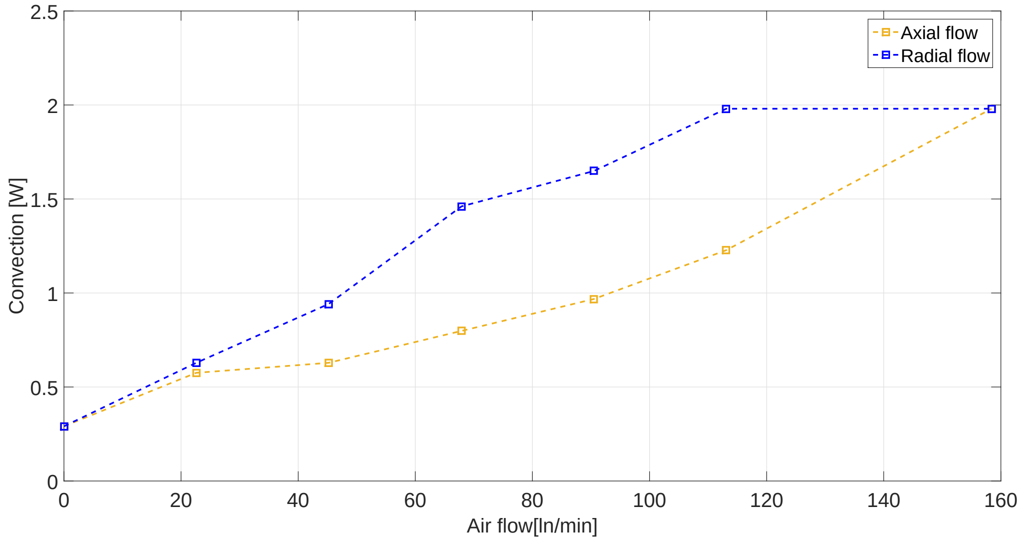


Figure B.4: Convection loss for axial and radial flow with a wolfram wire with diameter of 0.38 mm and a starting temperature of 488°C.

Appendix C

Equipment and serial numbers

Table C.1: Equipment names and serial number.

Name	Description	Serial number
MULTIMETER DIG RMS, FLUKE 112	Multimeter	S03-0353
RECTIFIER STAB REG, THURLBY THANDAR (TTI)	Current source	B02-0571
SMART MASS FLOW, BROOKS INSTRUMENT	Air flow generator	T26503/002
Read out & CONTROL ELECTRONICS, BROOKS INSTRUMENT	Air flow controller	T45083/001

Bibliography

[1] E.Jonsson and M. Runde. Interruption in air for different medium-voltage switching duties. *IEEE Transactions on Power Delivery*, 30(1):161–166, Feb 2015.

[2] F. Hao and Z. Junmin. Temperature rise comparison of switchgear in sf6, n2, and air. *TELKOMNIKA*, 2013.

[3] N. Khamshah, A. N. Abdalla, M. T. Ibrahim, D. Rifai, and S. R. Wahid. Temperature compensation of hot wire mass air flow sensor by using fuzzy temperature compensation scheme. *Scientific Research and Essays*, 2013.

[4] F. Kreith. *Principles of Heat Transfer.* International Textbook company, 1972.

[5] M. J. Moran and H. N. Shapiro. *Fundamentals of Engineering Thermodynamics.* Wiley, 2006.

[6] K. Niayesh and M. Runde. *Power Switch Compenents.* Springer, 2017.

[7] O. Nyhus. Air flow and arc cooling in load break switch. Specialization project, Norwegian University of Science and Technology, 2016.

[8] M. Runde. *Current Interruption in Power Grids.* Norwegian University of Science and Technology, 2015.

[9] Midwest Tungsten Service. Tungsten properties. *https://www.tungsten.com/materials/tungsten/*, 2016.

[10] T.M. Shih. *Numerical Heat Transfer.* Hemisphere Publishing Corporation, 1984.

[11] N. Støa-Aanensen, M. Runde, and A. D. Teigset. Arcing voltage for a medium-voltage air load break switch. *2015 IEEE 61st Holm Conference on Electrical Contacts (Holm)*, pages 101–106, 2015.

[12] R. L. Weber. *HEAT and TEMPERATURE MEASURMENT*. PRENTICE-HALL, 1950.