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Theoretical temperature model with experimental validation for CLIC Accelerating Structures

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Bachelor of Automation Engineering

Theoretical temperature model with experimental validation for CLIC Accelerating Structures

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Abstract

Micron level stability of the Compact Linear Collider (CLIC) components is one of the main requirements to meet the luminosity goal for the future 48 *km* long underground linear accelerator. The radio frequency (RF) power used for beam acceleration causes heat generation within the aligned structures, resulting in mechanical movements and structural deformations. A dedicated control of the air- and water- cooling system in the tunnel is therefore crucial to improve alignment accuracy.

This thesis investigates the thermo-mechanical behavior of the CLIC Accelerating Structure (AS). In CLIC, the AS must be aligned to a precision of 10 μm . The thesis shows that a relatively simple theoretical model can be used within reasonable accuracy to predict the temperature response of an AS as a function of the applied RF power. During failure scenarios or maintenance interventions, the RF power is turned off resulting in no heat dissipation and decrease in the overall temperature of the components. The theoretical model is used to explore control approaches that can be used to limit the temperature changes during such scenarios. The component temperature is highly dependent on the flow rate of the cooling water. The effect of active control of the water cooling flow rate to decrease temperature changes during failure scenarios (breakdowns) is investigated theoretically.

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Abbreviations

AS	A ccelerating S tructure
CLIC	C ompact L inear C ollider
CERN	C onseil E urpèen pour la R echerche N ucléaire
CTF3	C LIC T est F acility 3
DB	D rive B eam
DBQ	D rive B eam Q uadropole
MBQ	M ain B eam Q uadropole
LHC	L arge H adron C ollider
linac	L inear A ccelerator
MB	M ain B eam
PETS	P ower E xtraction and T ransfer S tructure
RF	R adio F requency
WG	W aveguide

Symbols

symbol	name	unit
A	surface area	m^2
C	specific heat	$kJ/kg\ ^\circ C$
h	heat transfer coefficient	$W/m^2\ ^\circ C$
k	thermal conductivity	$W/m\ ^\circ C$
L_c	characteristic length	m
m	mass	kg
$\dot{m}$	rate of mass flow	kg/s
Nu	Nusselt number	
P	power	$W(Js^{-1})$
Q	quantity of heat	kJ
$\dot{Q}$	rate of heat transfer	$W(Js^{-1})$
T	temperature	$^\circ C$
T_{cu}	AS component temperature	$^\circ C$
T_i	inlet temperature	$^\circ C$
T_e	outlet temperature	$^\circ C$
T_∞	ambient temperature	$^\circ C$
t	time	s
v	velocity	m/s
ρ	fluid density	kg/m^3

Chapter 1

Introduction

European Organization for Nuclear Science (Conseil européen pour la recherche nucléaire), CERN, is the world's largest research facility for high energy physics. At CERN, engineers and physicists work together to explore the fundamental structure of the universe. To study the basic constituents of matter, CERN use some of the world's largest particle accelerators. By accelerating particles to nearly the speed of light and putting them into collision, physicists are able to test their theories and explore the fundamental laws of nature [4].

1.1 Background

With a goal of uniting European scientists and share the costs of high energy physics facilities, CERN was established in 1954 [4]. The research facility is based in Geneva close to the Franco-Swiss border. Today, CERN consists of a total of 22 member states, but also other non-European countries are involved in the different research programs. There are 2500 people (as of 2016) employed directly by CERN, and around 12 000 visiting scientists from other organizations and universities are using the CERN facilities [5]

CERN's main purpose is to develop accelerator physics technology and run the large particle accelerator complex. Each accelerator boosts the energy of a particle beam, before injecting the beam into the next machine in the sequence. The last element in the chain is the world's biggest particle accelerator, the Large Hadron Collider (LHC) [6]. LHC has been in operation by CERN since September 2008 [7]. The accelerator is

placed 100 *m* underground, and has a circumference of 27 *km* with four main collision points spread out along the circle. LHC has produced billions of particle collisions, which have contributed to our understanding of the universe. Especially the discovery of the Higgs Boson in 2012 [8], which was predicted by Peter Higgs almost 60 years earlier [9].

In a circular accelerator like LHC, the particle beam loses energy through the emission of electromagnetic radiation when forced along the curved line. Acceleration along a straight line on the other hand, makes it possible to avoid these losses. To complement the LHC, the design of a future 48 *km* long linear electron-positron collider is being investigated. The Compact Linear Collider, CLIC, is under development and the technology is being tested at the CLIC test facilities at CERN [10].

1.2 Basic features of CLIC

CLIC foresees the use of strong accelerating fields to accelerate electrons and positrons to high enough energies to investigate very accurately production of new particles. The collisions take place in the middle of two linear accelerators, linacs, where the detector will be installed [11]. According to the CLIC Conceptual Design Report [1], the CLIC accelerator will be installed in a 48.3 *km* long underground tunnel. The CLIC complex is illustrated in figure 1.1.

The accelerator is divided into two meter long modules, consisting of the different components such as magnets, vacuum manifolds, power extracting units (PETS) and accelerating structures (AS), required to transport the beam.

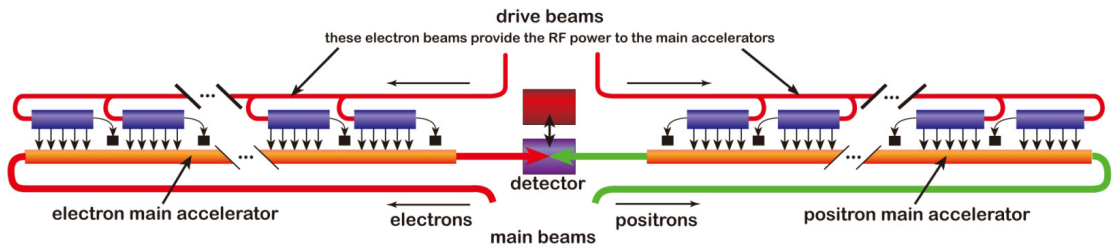


FIGURE 1.1: The CLIC main beam is accelerated by radio-frequency (RF) waves that are generated by a powerful electron beam (Drive beam) that runs parallel to the main beam [1].

The CLIC design is based on a two-beam acceleration scheme, as illustrated in figure 1.2. Two-beam acceleration means that the electrons and positrons are accelerated in

the main beam (MB) accelerating structures, powered by a high-intensity electron drive beam (DB) that runs parallel with the main linac. The basic concept is to transfer the energy from the DB to the MB using RF technology [1]. The beam is decelerated in the DB structure, generating RF power. The Power Extracting Units (PETS) transfer the energy to the MB accelerating structures, where it is used to accelerate the electrons and positrons towards the interaction point. The beam is focused by using quadrupole magnets which are situated along the whole length of the linac. A specialized particle detector will surround the interaction point to record the fine details of the collisions.

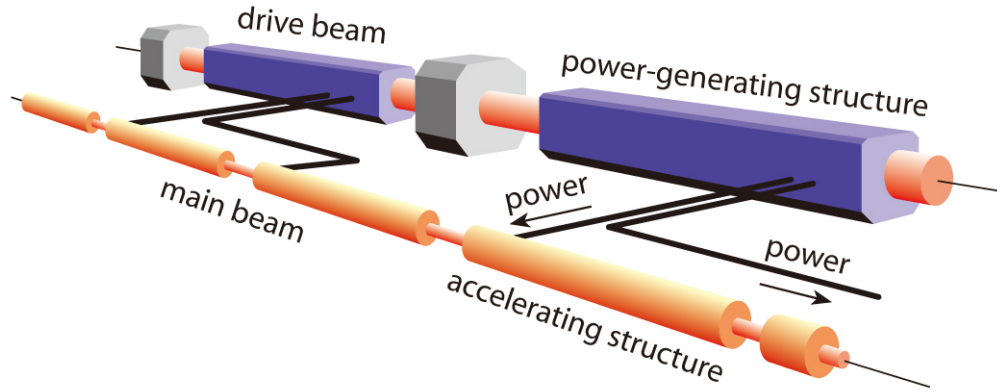


FIGURE 1.2: The CLIC two-beam acceleration scheme [1].

1.3 Aim of the study

CLIC technology requires micron precision alignment of the modules for successful passage of the beam. Deformations and movements in and between the components affect the beam quality resulting in reducing the luminosity¹. The AS components must be aligned to a precision of $10\ \mu$ [13], to ensure required beam quality.

Figure 1.3 show the CLIC mechanical test modules with mock up components in a dedicated Lab for thermo-mechanical, alignment and integration testing [13].

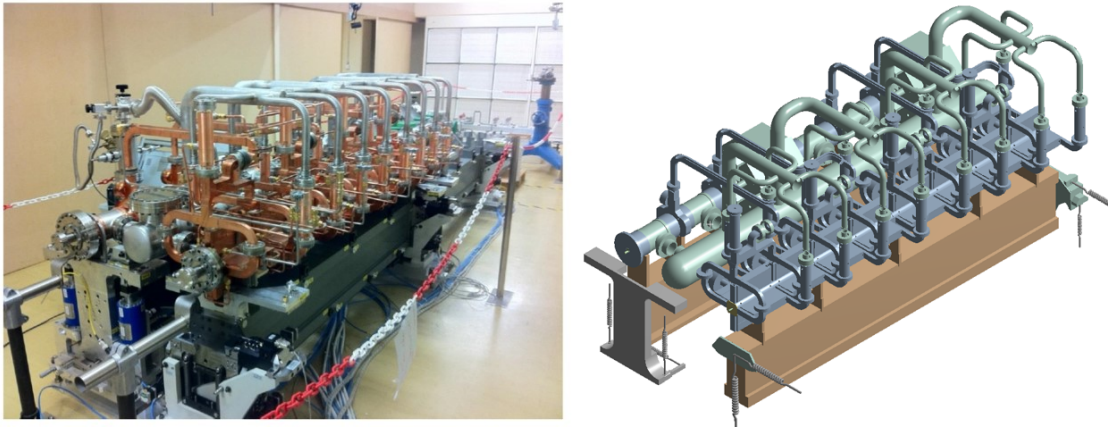


FIGURE 1.3: Left: The Two Beam Module mechanical model in the lab. Right: Simplified 3D model.

Heat dissipation within the structures affect the alignment in and between the different components. Temperature has been proved to be directly related to the mechanical displacement in the Two Beam Module [2]. The results shows that the transient displacement of a point P follows the temperature dynamics. Figure 1.4 shows the experimental results of position and temperature measurements completed at the Two Beam Module.

Due to this correlation between position and temperature, temperature fluctuations must be kept to a minimum to prevent structural deformations and movements due to thermal expansion of the material. Table 1.1 shows the relationship between ΔT and position of the point P.

¹"The quantity that measures the ability of a particle accelerator to produce the required number of interactions is called the luminosity and is the proportionality factor between the number of events per second and the cross section" [12]

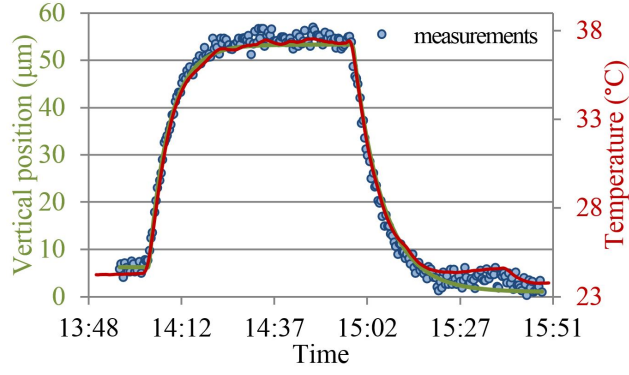


FIGURE 1.4: Position measurement of AS point P and best-fit line plotted against AS temperature [2].

TABLE 1.1: Temperature (ΔT) and displacement of one point (ΔX)

	$\Delta T (^{\circ}C)$	$\Delta X (\mu m)$
Power-up	5	50
Power-down	5	55

Further investigations are needed to understand how the different parts of the accelerator behave in terms of thermo-mechanical movements, individually and with respect to each other.

The aim of this thesis is to extend the knowledge regarding the temperature behavior of the CLIC AS. This is done by developing a differential equation to describe the temperature evolution over time. The model can easily be validated against experimental results from an AS installed in the CLIC test facility (CTF3). A realistic model facilitates the understanding of the influence of different factors, such as ambient temperature and water flow. The model can then be used to predict the effect of temperature control solutions. From the results in Table 1.1, it can be seen that decreasing the temperature with as little as $1^{\circ}C$ will reduce the vertical position of the point P with more than $10\mu m$.

This thesis provides a description of the thermo-mechanical behavior of CLIC AS, related theory and theoretical modeling supported by experimental results. The overview presented in Chapter 2 provides a brief introduction to the CLIC test facilities and the basic features of the AS. Thermodynamical concepts required for a general understanding of the temperature behavior of an AS are presented in Chapter 3. Chapter 4 describes the temperature Unit Step response of the AS, based on previous studies[2], followed by a numerical approach required for more complex solutions. In Chapter 5 the numerical model is compared to experimental data from the CTF3 experiment at

CERN. Chapter 6 explores ideas on how the water cooling system can be used control the temperature of an AS. Finally, in Chapter 7 the work is concluded and future work is suggested.

Chapter 2

System Overview

To investigate the principles of CLIC technology, CERN developed the CLIC Test Facility 3, CTF3. The layout and a picture of the two beam test stand in CTF3 is shown in Fig. 2.1. The objectives of the test facility were to test the drive beam production, RF power production and the two beam acceleration scheme in a scaled version [14]. CTF3 has successfully demonstrated these concepts [15].

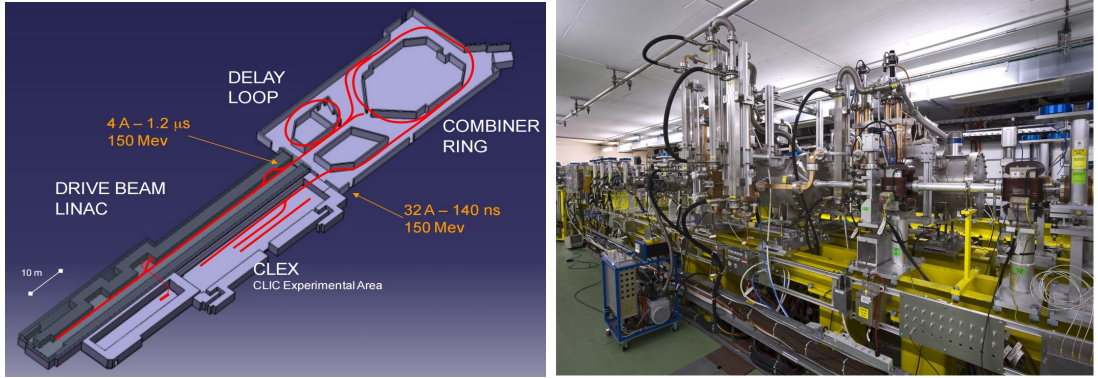


FIGURE 2.1: Left: Layout of CTF3. Right: The two-beam test stand in CTF3 [3]

2.1 The CLIC main linac Accelerating Structure

The beam is accelerated in the ASs. The AS comprises a stack of disks, made of oxygen-free electronic (OFE) copper. The disks are connected together by diffusion bonding at temperatures close to the melting temperature of the material 1083°C [16]. Fig. 2.2

show a 3D view of one single CLIC AS, followed by a picture of an Super AS ¹(SAS) installed in a CLIC test facility.

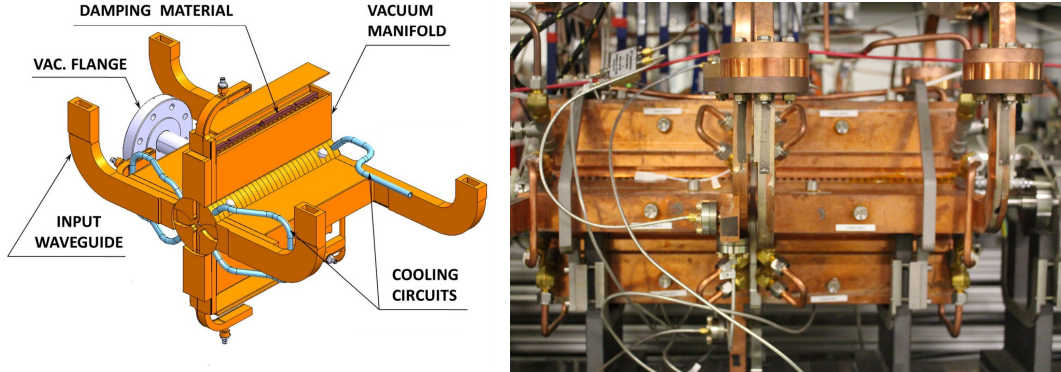


FIGURE 2.2: Left: CLIC Accelerating Structure [1]. Right: CLIC Accelerating structure in test facility

2.2 RF Breakdown

To build a machine at reasonable cost and size, and still reach a Multi-TeV range, CLIC requires an accelerating gradient of 100 MV/m [1]. Increasing the electric field in the AS also increase the likelihood for breakdowns within the structure. An RF breakdown is an electric arc caused in the vacuum by the electromagnetic field. Although vacuum breakdowns have been studied for over 100 years [17], there is still uncertainties regarding what really provokes the breakdowns. However, field emission sites are believed to be the main trigger of breakdown events. They are made from small ($17 - 25 \text{ nm}$) geometric deformities on the copper surface, which are able to enhance the local electric field 50–100 times, producing local gradients as high as 10 GV/m [18]. CERN hosts dedicated projects to study the factors affecting the breakdown rate [19]. However, for the purpose of this thesis, a breakdown can be seen as a short failure scenario, where the RF power is instantly turned off to prevent damage of the structure.

2.3 The Cooling system

Parts of the RF power used to accelerate the beam is lost due to heat dissipation because of ohmic losses within the accelerator, hence, CLIC requires a well defined water- and air

¹One SAS is two AS placed after each other in the beam direction

cooling system. To extract heat generated in the components, the system is cooled with integrated water cooling pipes made of copper. Each AS has an independent cooling channel, and most of the heat is removed by the water cooling system (copper to water). The remaining heat is transferred into air from the outer surfaces of the module via convection (copper to air). The surface of the AS from which heat can be transferred to air is 0.1 m^2 [2].

Chapter 3

Theory

Heat can be transferred from one system to another as a result of temperature difference, and problems dealing with the rate of such transfers is referred to as heat transfer. When analysing the thermal behaviour of an object, the amount of heat transferred is referred to as Q . However, it is often more useful to consider the rate of heat transfer, (heat transferred per unit time), denoted $\dot{Q}$, measured in J/s or W . When $\dot{Q}$ varies with time, the quantity of heat that is transferred during a process can be found by integrating $\dot{Q}$ over the chosen time interval [20]:

$$Q = \int \dot{Q} dt \quad [\text{kJ}] \quad (3.1)$$

The first law of thermodynamics states that energy can neither be created nor destroyed; it can only change forms. Therefore, every bit of energy must be accounted for during a process. When there is heat transfer only, and no work interactions the energy becomes [20]

$$Q = mC_v\Delta T \quad (\text{J}) \quad (3.2)$$

Specific heat (C)

Specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree. At constant volume, referred to as C_v , and at constant

pressure as C_p . The most common unit for specific heat is $kJ/kg^\circ C$ [20], and can be expressed in differential form as [21]:

$$C_p = \frac{(dQ)_p}{dT} \equiv \left(\frac{\partial Q}{\partial T} \right)_p$$

$$C_v = \frac{(dQ)_v}{dT} \equiv \left(\frac{\partial Q}{\partial T} \right)_v$$

where $(dQ)_p$ and $(dQ)_v$ are heat supplied at constant pressure and constant volume respectively.

3.1 Heat transfer mechanisms

The basic mechanisms of heat transfer are conduction, convection and radiation, these are explained in short in this section.

3.1.1 Conduction

Conduction is the transfer of energy from the more energetic molecules of a substance to the adjacent less energetic ones as a result of interactions between the particles [20]. When the molecules are heated, they transfer heat to nearby molecules, hence this process can occur in both fluids and solids. Rate of heat transfer due to conduction is described by Fourier's law of heat conduction as

$$\dot{Q}_{cond} = -kA \frac{dT}{dx} \quad (3.3)$$

where k is the thermal conductivity of the material, A is the area normal to the direction of heat transfer, and $\frac{dT}{dx}$ is the temperature gradient.

3.1.2 Convection

Convection is the transfer of heat that occurs between two substances moving relative to each other on a macroscopic level. Convection occurs in fluids in two ways; free and

forced convection. Free convection describes the spreading of particles from areas with high concentration to areas with lower concentration. Free (or natural) convection in air occurs when parts of the air comes in contact with a hotter or colder medium, and gets heated or cooled. Warm air will then raise, and create air flows. The principle of free convection is illustrated in Fig. 3.1.

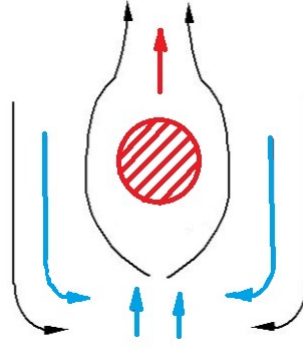


FIGURE 3.1: Free convection

Forced convection is caused by a fluid or air moving due to an external force, such as a fan or a pump. Convection is strongly dependent on parameters such as velocity and turbulence. In the case study presented in Chapter 5, only heat transfer due to free conduction is considered ($v_{air} = 0 \text{ m/s}$)

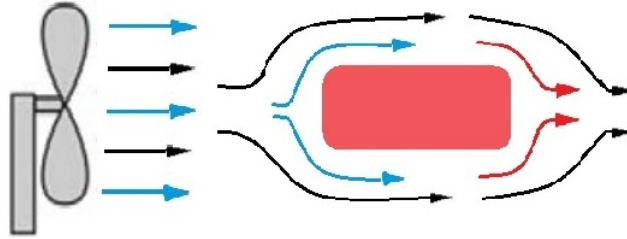


FIGURE 3.2: Forced convection

Newton's law of cooling states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings. The heat transfer due to convection is proportional to the surface and the fluid [22]. For an object with temperature T_S and area A with surrounding temperature of T_∞ the heat transfer from the liquid or gas to the solid object described by Newtons law of cooling as:

$$\dot{Q} = h_c A (T_S - T_\infty) \quad (\text{W}) \quad (3.4)$$

where the heat transfer coefficient h_c is an empirical value determined experimentally for different substances, flow situations and geometries. h_c is dependent on all variables that influence convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity. For free convection of gases, h_c are usually in the range of $2-25 \text{ W/m}^2 \cdot \text{K}$, and for forced convection of gases $25-500 \text{ W/m}^2 \cdot \text{K}$.

3.1.3 Radiation

The third main mechanism of heat transfer is radiation. All matter at a temperature higher than the absolute zero, emits thermal radiation due to the vibrational and rotational movements at a microscopic level. Radiation propagates in the form of electromagnetic waves, and is emitted from all points on a surface in all directions into the hemisphere above the surface. The quantity that describes the magnitude of radiation is the radiation intensity. Notice that the effect of radiation on the thermal behavior of the AS is not considered in the case study of this theses [20].

3.2 Steady-flow systems

Many systems involve mass flow in and out. These can be steady or transient. The mass flow is the amount of mass flowing per unit of time, and is denoted as:

$$\dot{m} = \rho v A_c \quad (\text{kg/s}) \quad (3.5)$$

where ρ is the fluid density, v is the average fluid velocity in the flow direction, and A_c is the cross-sectional area of the pipe. If the outgoing flow rate is equal to the incoming flow rate of mass, then $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$, as illustrated in Fig. 3.3 $T_1 T_2$

The rate of heat transfer of a steady flow system can then be described as [20]:

$$\dot{Q} = \dot{m} C_p \Delta T \quad (\text{kJ/s}) \quad (3.6)$$

$$\dot{Q} = \dot{m} C_p (T_e - T_i) \quad (\text{kJ/s}) \quad (3.7)$$

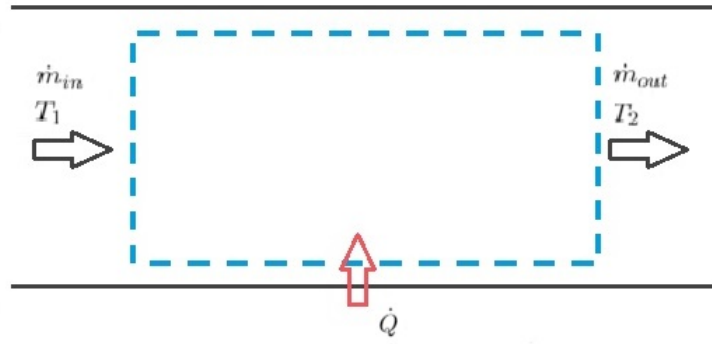


FIGURE 3.3: Inlet and outlet flow in steady flow system

where $\dot{Q}$ is the heat transfer rate, $\dot{m}$ is the mass flow rate, C_p is the specific heat of the fluid and ΔT is the temperature difference between the inlet and the outlet. T_i and T_e are the fluid temperatures at the inlet and the exit of the water pipes respectively.

3.3 Lumped system analysis

Until now, heat transfer has been described as independent of both time and position. In most cases the temperature of a body depends on when, as well as where in the solid it is measured. However, if the temperature of a solid varies with time but remains uniform throughout the solid at any time, it can be considered as a lumped system. With a lumped system analysis, the temperature of the body can be described without a reference to a specific location within the body. Thus, the temperature of the body is a function of time only, $T(x, t) = T(t)$ [20].

At $t = 0$ a block of material is placed in a room with surrounding temperature of T_∞ , the object itself has an initial temperature of T_i , mass m , volume V , surface area A , density ρ and specific heat C_p . During the time interval dt , the temperature changes by dT . Hence, the heat transferred into the object during this time, must equal the increase in the energy of the object during the same time interval.

$$hA_{surface}(T_\infty - T)dt = mC_p dT \quad (3.8)$$

The rate of convection heat transfer between the body and its environment can then be determined from Newton's law of cooling as

$$\dot{Q}(t) = h_c A (T(t) - T_\infty) \quad (\text{W}) \quad (3.9)$$

3.3.1 Criteria for lumped system analysis

The lumped system analysis is a convenient simplification to solve transient heating and cooling problems. It is therefore important to investigate if this assumption can be used and still provides a reasonable accuracy.

When dealing with conduction problems involving surface convection effects, it is useful to define a dimensionless parameter called the Biot number[23]. The Biot number describes the relationship between the convection at the surface of the body and the conduction within the body. Hence, a Biot number less than one means that the resistance to conduction within the solid is less than the convection at its boundary layer. Therefore, a Biot number equal to zero, is a perfect lumped system [20]. The error associated with lumped system analysis is considered small if $Bi < 0.1$ [23]:

$$Bi = \frac{hL_c}{k} < 0.1, \quad (3.10)$$

where k is the thermal conductivity of the solid and L_c is defined as the characteristic length L_c as

$$L_c = \frac{V}{A_s}.$$

3.3.2 Biot number calculation for AS

An AS used in CTF3 has the mass $m = 16\text{kg}$, $A = 0.1\text{m}^2$, mass density $\rho = 8960\text{kg/m}^3$, heat transfer coefficient $h = 11\text{W/m}^2 \cdot ^\circ\text{C}$ and $k = 401\text{W/m} \cdot ^\circ\text{C}$. This gives the characteristic length:

$$L_c = \frac{V}{A_s} = \frac{1}{56} \text{m}.$$

Then the Biot number becomes

$$Bi = \frac{hL_c}{k} = \frac{11 \text{ W/m}^2 \cdot ^\circ \text{C} \cdot \frac{1}{56} \text{ m}}{401 \text{ W/m} \cdot ^\circ \text{C}} = 0.00067.$$

$$0.00067 \ll 0.1$$

In a block of copper, the temperature can be considered uniform through out the body [20]. The heating of an accelerating structure satisfies the criteria for the lumped system analysis.

3.4 Unit Step Response

The unit step, $u_s(t)$, is the simplest function used to analyse the system's response due to an instant change in its input, and is defined as

$$f(t) = u_s(t) = \begin{cases} 0 & t < 0 \\ 1 & t \geq 0. \end{cases}$$

The unit step response to a first order differential equation, can be found by converting to state space, and taking the inverse Laplace transform. For a first order differential equation

$$y'(t) + y(t) = f(t) \quad (3.11)$$

the response can be found as follows:

$$\begin{aligned} y'(t) + y(t) &= 1 \\ sY(s) + Y(s) &= \frac{1}{s} \\ Y(s) &= \frac{1}{s(s+1)} \\ \mathcal{L}^{-1}\{Y(s)\} &= \mathcal{L}^{-1}\left\{\frac{1}{s}\right\} + \mathcal{L}^{-1}\left\{\frac{-1}{(s+1)}\right\} \\ y(t) &= 1 - e^{-t} \end{aligned} \quad (3.12)$$

with zero initial conditions, the input and output of the above example is plotted in Fig. 3.4

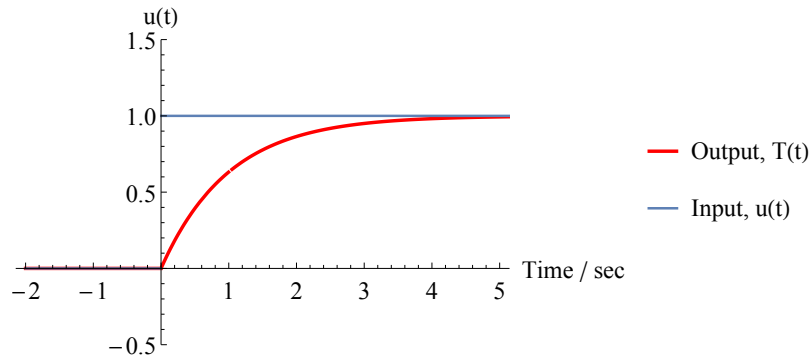


FIGURE 3.4: Unit step input and output

Chapter 4

First-Order System Transient Response

The response of a first order system can be calculated due to a defined or known input, $f(t)$. In testing situations, simple functions such as the step or ramp input are commonly used. However, with numerical tools, it is possible to solve the differential equation with a more complicated forcing term. In the following chapters, several different inputs are investigated. The main focus is on the system response to a step function and to a real RF power signal.

4.1 Theoretical analysis

For simplicity, the RF power can be divided in two; the part used for acceleration, and the part that is dissipated as heat. The part of the RF power dissipated as heat, is proportional to the rate of heat transfer $\dot{Q}_h$ from the structure, and is assumed to be distributed among the AS material (copper) as $\dot{Q}_{cu}$, the water cooling pipes $\dot{Q}_{water}$ and the air $\dot{Q}_{air}$:

$$\dot{Q}_h = \dot{Q}_{cu} + \dot{Q}_{water} + \dot{Q}_{air}. \quad (4.1)$$

The RF power is time dependent and $\dot{Q} = \dot{Q}(t)$. When applying a lumped system analysis, there is no reference to position. The rate of heat transfer at any time for each component can then be defined as follow [1]:

$$\begin{aligned}
\text{To copper :} \quad \dot{Q}_{cu}(t) &= m_{cu} C_{p,cu} \frac{dT_{cu}}{dt} \\
\text{To water :} \quad \dot{Q}_{water}(t) &= \dot{m}_w C_{p,w} [T_w(t) - T_w(0)] \\
\text{To air :} \quad \dot{Q}_{air}(t) &= h A_{cu} [T_{cu}(t) - T_\infty]
\end{aligned} \tag{4.2}$$

where $c_{p,x}$ the heat capacity, m_{cu} the AS mass, A_{cu} the AS surface, $\dot{m}$ the water mass flow, h the heat transfer coefficient, and T_∞ , T_{cu} and T_w the ambient, AS and outlet water temperatures respectively [2].

From the Eq(4.2), the total heat flow from the structure can be written as:

$$\dot{Q}_h(t) = m_{cu} c_{p,cu} \frac{dT_{cu}}{dt} + \dot{m}_w c_{p,w} [T_w(t) - T_w(0)] + h A_{cu} [T_{cu}(t) - T_\infty]. \tag{4.3}$$

The component and outlet temperature of an AS differs by $\approx 1^\circ C$ [2]. The two are considered equal through out this analysis, and hence $T_{cu}(t) = T_w(t)$. Defining $A = m_{cu} c_{p,cu}$ $B = \dot{m}_w c_{p,w}$ $C = h A_{cu}$, this gives a first order differential equation:

$$\boxed{\dot{Q}_h(t) = A \frac{dT_{cu}}{dt} + (B + C) T_{cu}(t) + (-B T_w(0) - C T_\infty)} \tag{4.4}$$

This equation may be written in the standard form by dividing both sides by $(B + C)$:

$$\frac{\dot{Q}_h(t)}{(B + C)} = \frac{A}{(B + C)} \frac{dT_{cu}}{dt} + T_{cu}(t) + \frac{(-B T_w(0) - C T_\infty)}{(B + C)} \tag{4.5}$$

From Eq(4.5), the time constant of the system can be written as

$$\tau = \frac{A}{(B + C)} = \frac{m_{cu} c_{p,cu}}{\dot{m}_w c_{p,w} + h A_{cu}}, \tag{4.6}$$

where the time constant is defined as the time a first-order system requires to complete 62.3% of the total raise or decay (the steady state) [24].

Notice from Eq.(4.6), that the time constant of the system is independent of the dissipated power. It depends upon the cooling water flow rate, object mass, object surface

area, the heat capacity of copper and water, and the heat transfer coefficient of the object in air.

4.2 The Step response

If the power is either ON or OFF, the forcing term in the differential equation can be treated as a step input. The temperature response of an AS can then be found with the same steps as for the first order unit step response. The solution to the differential equation (Eq.(4.4)) describing the heat transfer from an AS follows:

With a time independent forcing term, $\dot{Q}_h(t) = \dot{Q}_h$, Eq.(4.4) simplifies to:

$$A \frac{dT_{cu}}{dt} + (B + C)T_{cu}(t) + (-BT_w(0) - CT_\infty - \dot{Q}_h) = 0 \quad (4.7)$$

$$\boxed{D = \frac{(B + C)}{A}, K = \frac{(-BT_w(0) - CT_\infty - \dot{Q}_h)}{A}} \quad (4.8)$$

$$\begin{aligned} \frac{dT_{cu}}{dt} + DT_{cu}(t) + K &= 0 \\ \frac{dT_{cu}}{dt} + DT_{cu}(t) &= -K \end{aligned} \quad (4.9)$$

The unit step response is then found by converting to state space, and multiply the constant by the state space equivalent to the unit step, $\frac{1}{s}$:

$$\begin{aligned} sT_{cu}(s) + DT_{cu}(s) &= -\frac{1}{s}K \\ T_{cu}(s)(s + D) &= -\frac{K}{s} \\ T_{cu}(s) &= -\frac{K}{s} \cdot \frac{1}{s + D} \end{aligned} \quad (4.10)$$

using the Partial Fraction Expansion to obtain expressions that have a simple inverse Laplace transforms:

$$\begin{aligned} -\frac{K}{s(s + D)} &= \frac{A}{s + D} + \frac{B}{s} \\ As + B(s + D) &= -K \end{aligned} \quad (4.11)$$

$$\begin{aligned}
 (s = 0) \quad BD = -K &\longrightarrow B = -\frac{K}{D} \\
 (s = -D) \quad -AD = -K &\longrightarrow A = \frac{K}{D}
 \end{aligned}
 \tag{4.12}$$

$$T_{cu}(s) = \frac{\frac{K}{D}}{(s + D)} + \frac{\frac{-K}{D}}{s}$$

Finally, taking the inverse Laplace transform:

$$\mathcal{L}^{-1}\{T_{cu}(s)\} = \mathcal{L}^{-1}\left\{\frac{\frac{K}{D}}{(s + D)}\right\} + \mathcal{L}^{-1}\left\{\frac{\frac{-K}{D}}{(s)}\right\}$$

The analytic solution of Eq(4.9) reads [2]:

$$T_{cu}(t) = -\frac{K}{D}e^{-Dt} + \frac{K}{D} \tag{4.13}$$

With Eq.(4.13), the previous prediction of the time constant is confirmed, as $\tau = \frac{1}{D}$, and the time constant is

$$\tau = \frac{1}{D} = \frac{1}{\frac{B+C}{A}} = \frac{A}{B+C} = \frac{m_{cu}c_{p,cu}}{\dot{m}_w c_{p,w} + hA_{cu}}. \tag{4.14}$$

For an AS with mass $m_{cu} = 16kg$, cooling water flow $\dot{m} = 0.025kg/sec$, surface area $A_{cu} = 0.1m^2$, the time constant is approximately one minute. In Fig.4.1 the step response for ambient temperature off $20^\circ C$ is plotted.

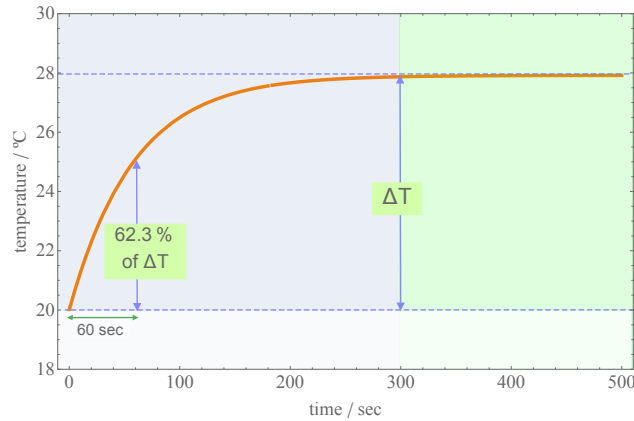


FIGURE 4.1: Step response of AS with $20^\circ C$ as initial condition

4.3 Complex forcing terms

Solving Eq.(4.4) with respect to a time dependent forcing term, $\dot{Q}_h(t)$ is complex and cannot be solved with simple mathematical steps. Mathematica has been used to produce a numerical solution to the differential equation using the ND solve function [25] (the Mathematica notebook can be found in Appendix B).

The RF power pulses used for beam acceleration in the Dog-leg experiment is recorded. Subtracting the amount used to accelerate the beam, the resulting function is the power dissipated as heat. This function of power over time is used as the input when calculating the theoretical temperature response of the structure. Fig.4.2 shows the heat generation (the system input) in red to the left and the theoretical solution as obtained in Mathematica in blue to the right.

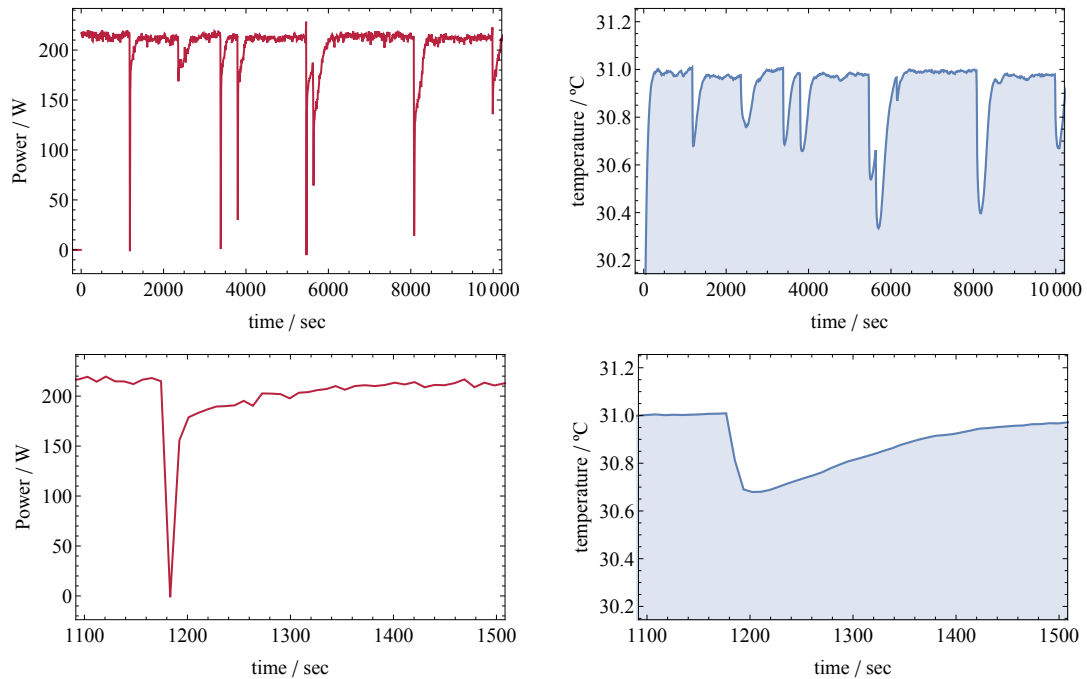


FIGURE 4.2: Examples of heat generated by RF power in red and the expected system responses in blue

Chapter 5

Experimental Setup and Results

In this chapter, the experimental setup and results are presented. The experimental results are also compared to the theoretical prediction from Chapter 4.

5.1 Temperature recordings

RTD temperature sensors (PT 100, 4-wire resistance) are used for measuring temperature during operation. The sensor accuracy is $\pm 0.1^\circ\text{C}$. Fig. 5.1 show the RTD sensor installed on the AS in the Dog-leg experiment.

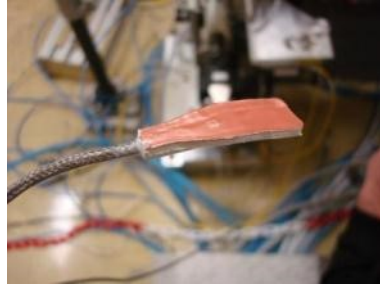


FIGURE 5.1: RTD sensors with integrated double-sided tape

The three temperature sensors are installed on the AS as shown in Fig. 5.2. The inlet and outlet sensors are taped directly on the water pipe, and is a indirect measure of the water temperatures trough the copper pipe. The component sensor is taped on the structure, and is a measure of the copper itself. Both the inlet and ambient temperatures are ideally kept constant at $T_{in} = 28^\circ\text{C}$ and $T_{amb} = 20^\circ\text{C}$, respectively. The ambient temperature is assumed constant throughout this analysis.

The experimental temperatures recorded are:

- inlet water temperature, T_{in}
- component temperature, T_{comp}
- water temperature, T_{out}

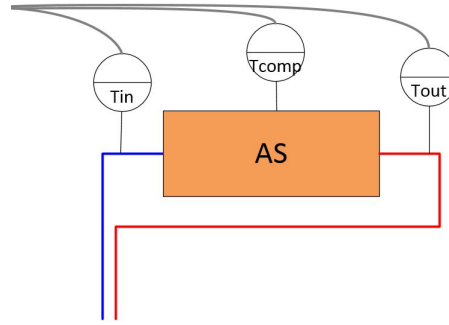


FIGURE 5.2: Position for inlet, component and outlet temperature sensors AS

Temperature filtering

Water is cooled and supplied by a water chiller. Variations in the temperature of the water supplied by the chiller cause tracking errors in the temperature recordings of the component and outlet temperature.

The cooling water temperature varies with up to $\approx \pm 0.5^\circ C$. Naturally, the temperature of the component itself and the outlet water temperature varies accordingly. It is important to separate the temperature variations caused by a varying T_{in} temperature, and the temperature change of interest - the temperature response due to power dissipation in the structure.

The tracking errors caused by the inlet water can be accounted for by subtracting the change in inlet temperature from the component and outlet temperature:

$$T_{\text{component filtered}} = T_{\text{component}} - T_{\text{in}} + T_{\text{in constant}}. \quad (5.1)$$

The effect of removing the tracing error is shown in Fig. 5.3. Notice how the component and outlet temperatures become more steady between the breakdowns.

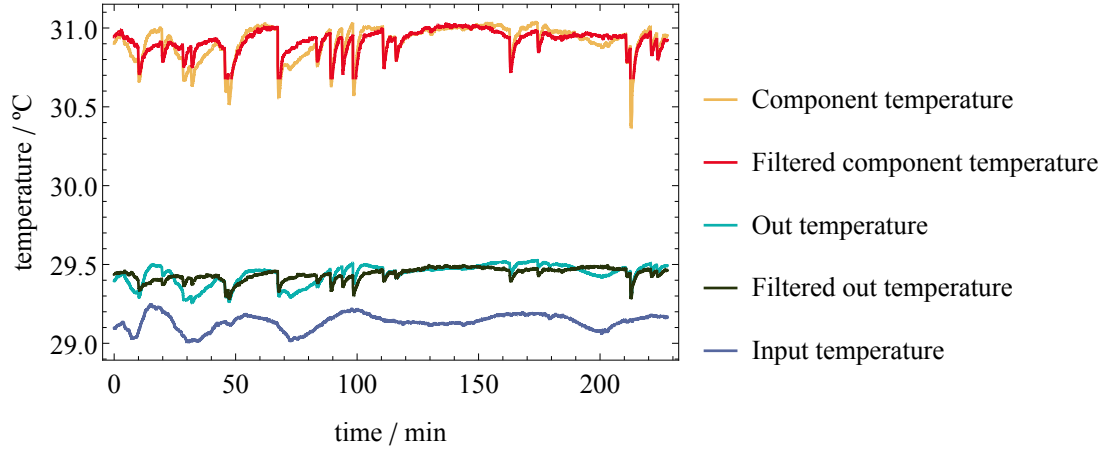


FIGURE 5.3: Effect of removing tracking errors in experimental temperature data

5.2 Operating conditions

The physical constants and relevant operating conditions are presented in table 5.1 and 5.2 respectively:

TABLE 5.1: Physical constants

	Unit	Value
Heat capacity water	$J/kg \cdot ^\circ C$	4184
Heat capacity copper	$J/kg \cdot ^\circ C$	386
Heat transfer coefficient	$W/m^2 \cdot ^\circ C$	11
Component surface	m^2	0.1
Component mass	kg	16

TABLE 5.2: Operating condition constants

	Symbol	Value
Air speed	v_{air}	$0 m/s$
Ambient temperature	T_∞	$20^\circ C$
Mass flow rate	m	$0.025 kg/s/$
Inlet temperature	T_i	$28^\circ C$
Heat generation AS	$\dot{Q}$	$200 - 820 W$

5.3 Experimental Results

In this section the experimental data is presented and compared to the mathematical model. In Fig. 5.4 and 5.5 the theoretical model is plotted in blue, together with the experimental temperature data in red. The sensor accuracy is $\pm 0.1^\circ\text{C}$, and is represented with error bars.

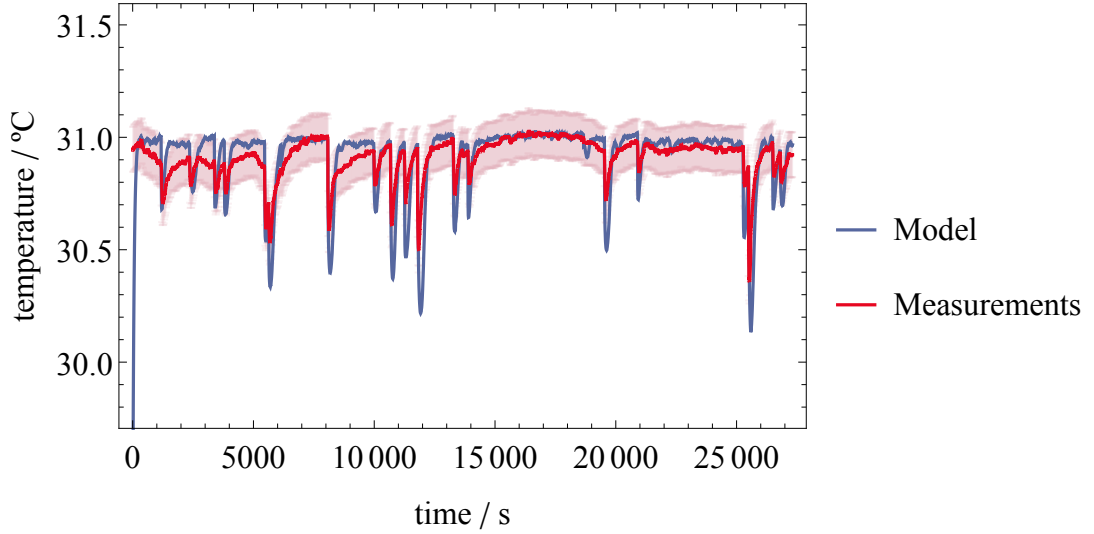


FIGURE 5.4: Theoretical model and measurements with error bars

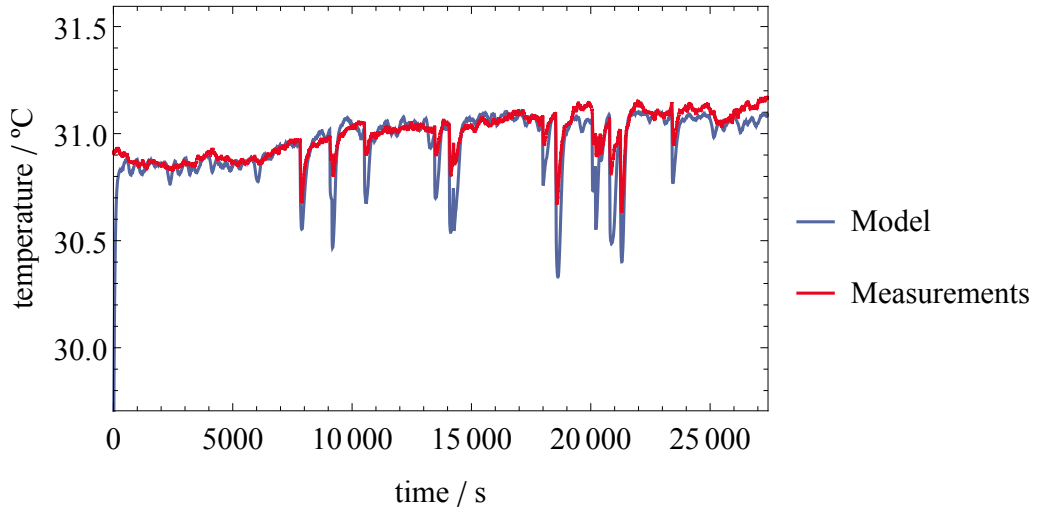


FIGURE 5.5: Theoretical model and measurements

The temperature of the component changes $0.5 - 2^\circ\text{C}$ during an RF breakdown, dependent on the operating conditions (beam or no beam). The model has shown to match experimental data for all data sets investigated in this analysis. Fig. 5.5 shows a different set of data, again over a time span of around 7 hours. The theoretical analysis

matches the experimental data, and hence the model can be used to predict temperature response under transient conditions within reasonable accuracy. This is investigated further in the following chapter. A reliable model opens the possibility to simulate possible scenarios and temperature control approaches. These results allows the use of the theoretical model developed in Mathematica (Appendix B) to investigate the temperature response in several possible scenarios.

Chapter 6

Water flow control

From the theoretical analysis, the time constant is found to be directly proportional to the material and geometry of the AS, and is inversely proportional to the water flow (Eq. (4.6)). A previous study completed by the CLIC module team on the relationship between thermal time constant and water flow shows that the two are largely correlated [2]. The experimental results from this study are illustrated in Fig. 6.1. It is shown that the time constant clearly decreases with increasing flow rate.

This observation introduces the possibility to control the temperature of an AS through appropriate regulation of the water flow. In this chapter, some ideas and possible theoretical solutions on the design of a dynamic water cooling system are presented.

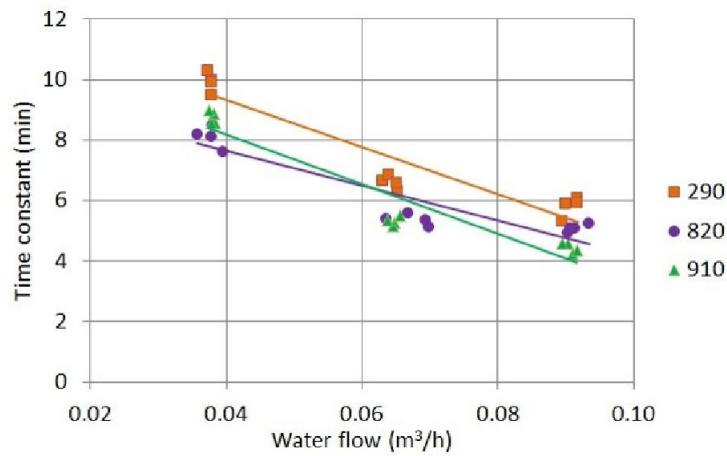


FIGURE 6.1: Time constants at increasing water flow, with an heat generation of 290 W, 830 W and 910 W [2]

6.1 Effect of water flow on temperature response

When increasing the flow rate, the average temperature of the AS decreases towards the temperature of the cooling water. As expected, the fall and raise time decrease with increasing flow rate. This effect is shown in Fig. 6.2, where the fall time changes with approximately 2 minutes when the flow changes from 0.02 kg/sec to 0.08 kg/sec , and the operating temperature decrease from 31.2°C to 29.6°C . However, such huge increase in the water flow rate is not realistic due to the capability of the water pipes and pumps.

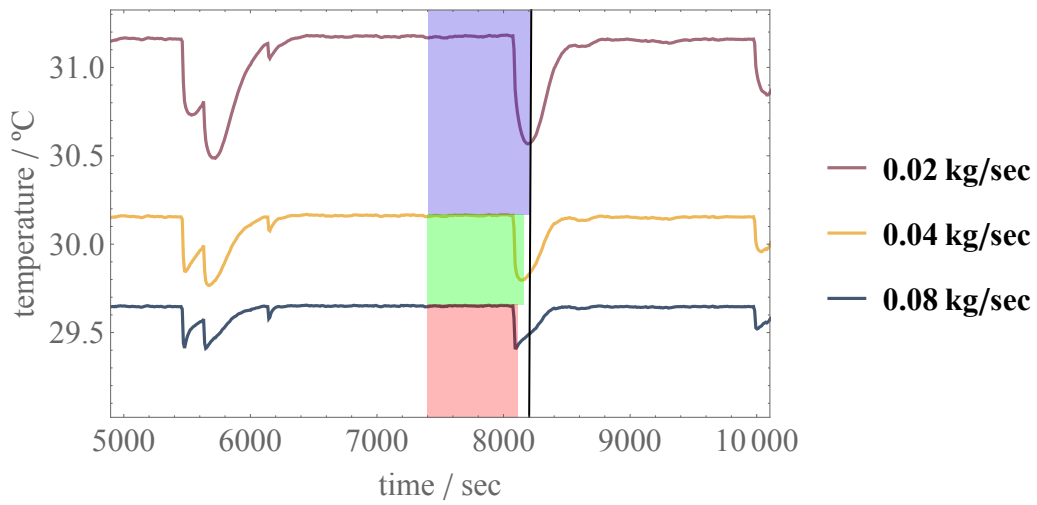


FIGURE 6.2: Temperature response for different water flow rates

Providing less cooling during times of decreased heat generation is the logical solution in terms of water cooling control. By defining a default water flow (determined by the system, $\approx 0.025 \text{ kg/sec}$ for Dog-Leg AS) during normal operation, and decreasing the flow according to a particular function during times of less heat production, is expected to limit temperature changes. The optimal solution would be to control the flow as a direct function of the dissipated power at all times. Another and more simple solution would be to use the same pre-defined routine when a breakdown is observed. These two suggestions are investigated further in the following sections.

6.2 Simple flow control

Due to restricted precision of the control valves, more simple control approaches are investigated in this section. It is possible to apply a pre-defined water flow routine each time a breakdown is recorded in the system. Fig. 6.3 shows the average heat dissipation during one breakdown as observed in the test facility.

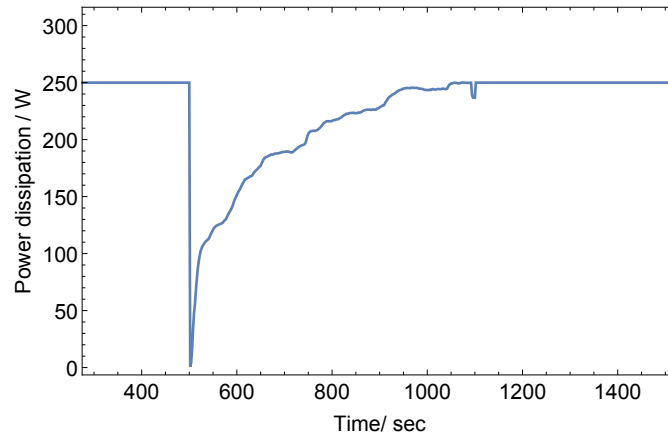


FIGURE 6.3: Power dissipated as heat during an average breakdown

The flow can be controlled in several possible ways. In the following examples the breakdown occurs at exactly $t = 500$. Fig. 6.4 presents some possible ways to control the flow rate during a breakdown. The purple function is the water flow, and the blue line represent the corresponding temperature response. The input in all examples is set as the average power dissipation during a breakdown (see Fig.6.3).

Consider for instance the most simple case; to turn the cooling on/off almost instantly. The response when the flow is simply turned off for 50 seconds, is presented as "100% off". Notice how the control actually causes the structure to increase the temperature above the steady state temperature. When the flow rate is only reduced by 50% on the other hand (referred to as 50% off), the structure is cooled down for the first ≈ 75 seconds, before the structure starts to heat up due to lack of sufficient cooling. However, in this case the temperature does not increase above its steady temperature, but it causes a small peak in the temperate at $t = 600$. These results indicates that decreasing the cooling drastically within a short time period (~ 50 sec), will actually cause an increase in component temperate, or undesired fluctuations.

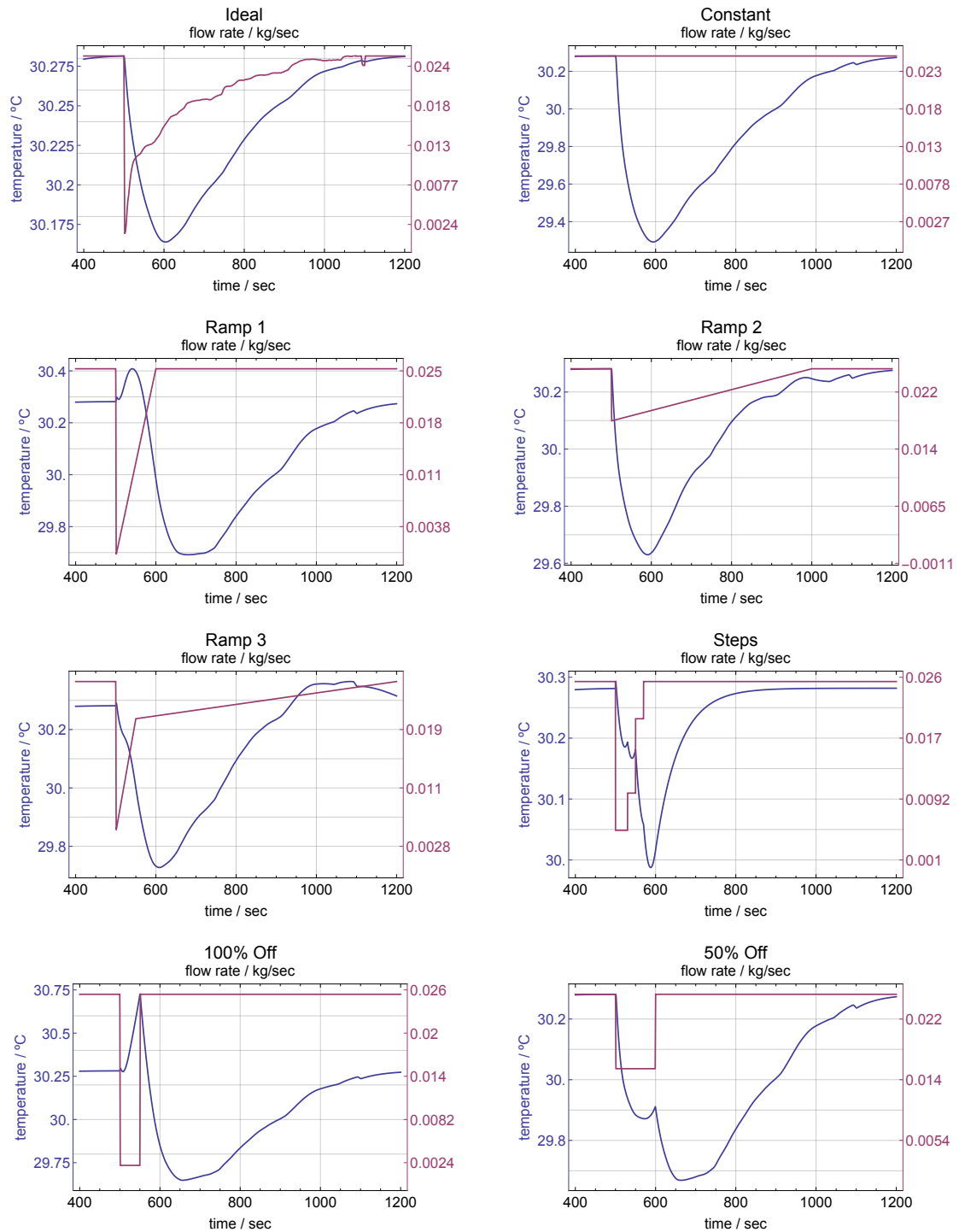


FIGURE 6.4: Water flow control with corresponding temperature response

The response for the different flow suggestions are plotted on top of each other for easier comparison in Fig.6.5.

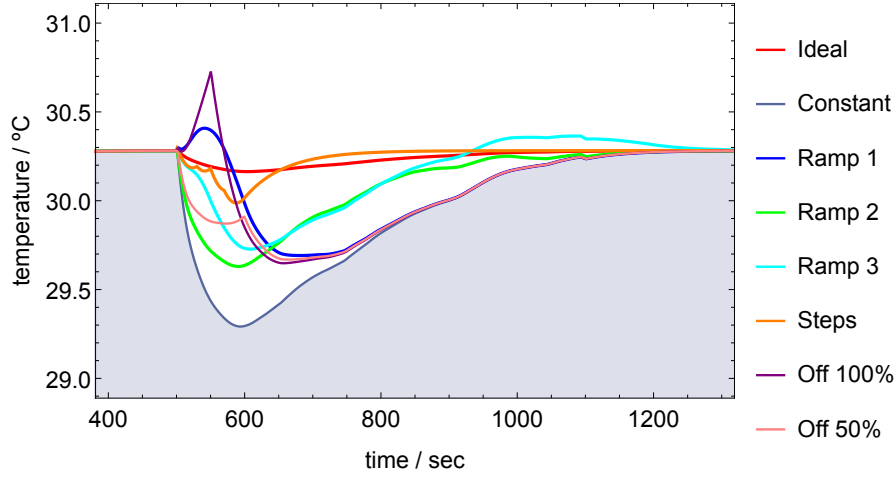


FIGURE 6.5: Temperature response for different flow control signals

- Ideal: the ideal temperature response (when the flow fitted to the heat generation at any time) is illustrated in red, and is clearly the preferred solution, as it is causing the minimum temperature variation.
- Ramp: Both ramp2 and ramp3 reduce the temperature change with approximately 50% compared to the constant flow (filled blue), without introducing dominant peaks. However, Ramp1, which linearly increase the flow rate over 100 seconds, gives insufficient cooling, and the structure temperature increase above the steady temperature.
- Steps: Stepping up the flow in several intervals, results in a small change in temperature. However, the response is not very smooth, and gives several small peaks in the temperature.
- On/off 100%: Turning the flow to zero during the breakdown actually provides too little cooling, and the structure is being heated. The same effect is predicted when the simplest ramp function is applied (dark blue).
- On/off 50%: Reducing the flow by 50% provokes a small peak in the temperature around $t = 600s$. However, it differs from the 100% on/off as it does not increase above the normal operation temperature.

6.3 Feedback flow control

The RF power can be used directly to determine the optimal water flow for minimizing temperature fluctuations. The left graph in Fig. 6.6 shows a typical RF power signal

over a time period of 4 hours. The same signal is used as the input signal in all the following examples.

The flow is obtained by scaling the RF power signal with a factor of X and adding a constant K . The ideal flow rate can then be expressed as: $flow(t) = \dot{Q}(t) \cdot X + K$. The resulting flow rate is shown to the right in Fig. 6.6. The scaling of the signal is clearly arbitrary and should be modified according to the requirements of the system and the capability of the cooling pipes .

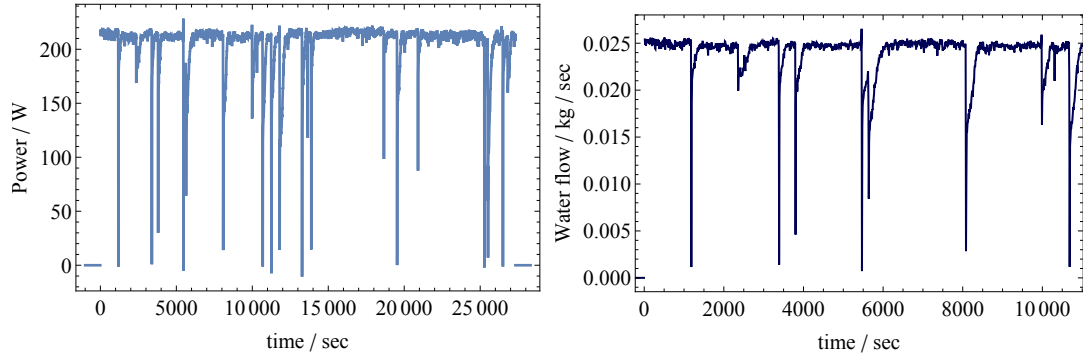


FIGURE 6.6: Left: Average power dissipated as heat. Right: Water flow signal as a function of heat generation.

Fig. 6.7 shows how the water flow algorithm successfully almost eliminates temperature fluctuations during breakdowns. The blue filled line is the model at a constant water flow ($= 0.025 \text{ kg/sec}$), and the black line presents the predicted response when applying the flow control. The difference between the two in this example is 0.8°C . As both models provides the system with same flow during normal operation, $= 0.025 \text{ kg/sec}$ in this example, they also predict the same structure temperature ($\approx 30.8^\circ\text{C}$) during normal operation.

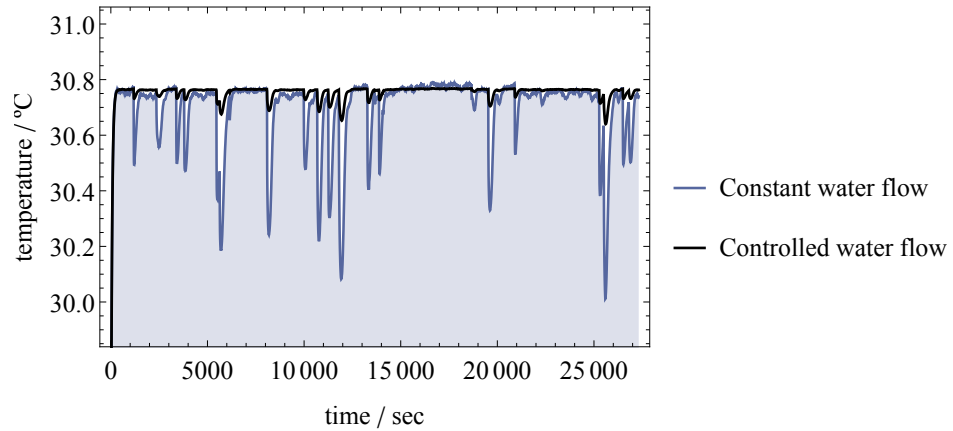


FIGURE 6.7: Theoretical temperature response with and without water flow control

6.4 Effect of system delay

In reality, it is not possible for the control valves to adjust instantly as assumed until now. A breakdown last on a scale of seconds, and the system takes about 2 – 3 minutes to recover back to its steady state temperature. It is therefore interesting to explore if it is realistic to benefit from a flow control before normal heat generation is reestablished after the breakdown.

The delay time is referred to as the reaction time from observed breakdown to the flow changes in the pipes in and around the structure. The electronics can be assumed to change instantly and the pressure in the pipes is constant. The delay time is therefore the time it takes for the valve to physically adjust to the chosen flow. To get a better understanding of tolerances in terms of reaction time, the effect of a delayed flow control signal is investigated.

Two signals with delay times of 1 and 10 seconds has been chosen for the flowing example. Fig. 6.8 shows the original water flow control signal in blue together with the delayed signals in orange and yellow. According to the RF signal, the breakdown starts at exactly $t = 500$, and the delayed signals will therefore act at $t = 501$ and $t = 510$. Every point in the function is delayed, shifting the whole function the right. In practical terms this means that the flow at a specific time is the flow that was perfectly fitted for the heat generated 1 or 10 seconds earlier.

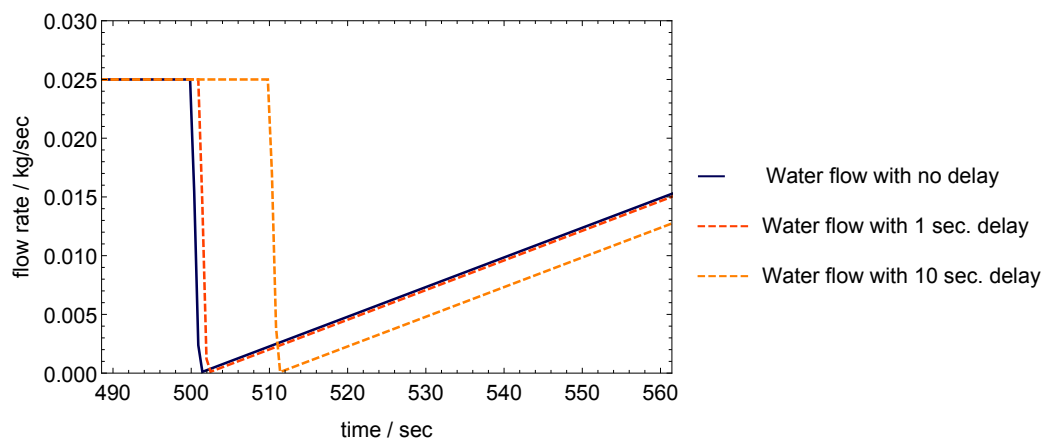


FIGURE 6.8: Instant(blue) and delayed (yellow) water flow control signal during one breakdown

In Fig. 6.9 a zoom shows the response based on instant feedback control against the delayed responses. The model behaves as expected, as the black instant control starts to

stabilize towards normal operation temperature at the exact moment when the breakdown occurs ($t = 500$). The orange line has a sudden drop at the breakdown point, before the control sets in and stabilizes the effect after 1 second at $t = 501$. The response to the 10 sec. delayed signal behaves similar to the constant flow response for the first 10 seconds, before the flow is decreased at $t = 510$, and the temperature increase towards the stable temperate. It also cause a small overshoot at $t = 600$ due to lack of cooling relative to heat dissipation at this moment. However, note that the overshoot is less than the accuracy of the temperature sensors ($0.1\text{ }^{\circ}\text{C}$) and will most likely not be noticeable in experimental tests.

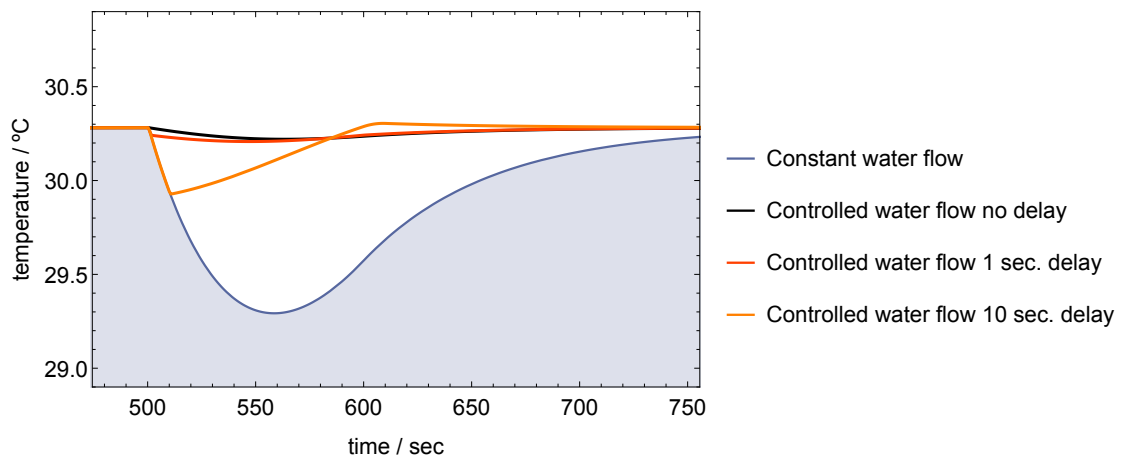


FIGURE 6.9: Model of temperature response with instant and delayed water flow control

The difference between the delayed and instant control is according to Fig. 6.9 less than $0.1\text{ }^{\circ}\text{C}$ when there is 1 second delay time, which in perspective is the same as the accuracy of the temperature sensor. A 10 sec. delay is not as effective, but the control still decrease temperature changes relative to no control with $0.5\text{ }^{\circ}\text{C}$. There seems to be no compelling reason to argue that a delay time in the system limits a sufficient water cooling control of an AS. Difficulties arise, however, due to other technical challenges. For example, it requires control valves capable of providing an accurate flow at any time.

Chapter 7

Conclusion and Future Work

Conclusions

This thesis outlines the work which was undertaken to investigate the theoretical and experimental thermal behavior of the CLIC AS. A simple but realistic model was developed and tested against experimental data. The temperature dynamics follow a first-order system behavior. A numerical solution obtained with Mathematica provides a model for the temperature evolution over time. The forcing term in the differential equation is the heat generation caused by beam acceleration, and is directly proportional to the applied RF-power. The model was then compared to experimental temperatures from the Dog-leg experiment. The modelling results are in compliance with the experimental data.

A realistic model facilitates the understanding of the influence of different factors, such as ambient temperature and water flow. Moreover, the model was used to qualify several approaches for water cooling control, in which especially one was found to be theoretically efficient. The most efficient control approach, referred to as "ideal flow", decreased temperature changes with $\sim 75\%$. Alignment measurements performed at the two beam module, shows that with a $\Delta T = 1^\circ C$, results in a vertical displacement of $\sim 10 \mu m$. With the temperature variation of $\Delta T = 4^\circ C$, this control approach results in reducing the vertical displacement of a point P (on the AS surface relative to the beam line) from $40 \mu m$ to $10 \mu m$. Considering the tight alignment tolerances of $10 \mu m$ for the CLIC AS, the solution suggested in this thesis can play a significant role in improving the overall

alignment of the CLIC components. However, it should be mentioned that controlling temperature with flow rate can introduce vibrations or other potential complications to the system.

Furthermore, the effect of a potential delay in the system was investigated. There seems to be no compelling reason to argue that a short delay time in the system limits a sufficient water cooling control of an AS. However, challenges arise due to other hardware limitations. For example, it requires control valves capable of providing an accurate flow at any time. How these techniques would work in reality is therefore relevant for future experimental investigation.

Future work

The use of a dedicated flow control to limit temperature changes in an AS should be evaluated experimentally.

Firstly, the capabilities of the valves should be tested in practice. A experimental characterization of the control valves will disclose the capability of precise water flow control. Thermal tests should be preformed to investigate the temperature response during different cooling scenarios. The thermal tests of the cooling approaches presented in this thesis are planned at the CLIC module test facility in 2017.

It is recommended to investigate the possibility of controlling the temperature of the accelerator over longer shut downs. During longer shut downs, the temperature will fluctuate between ambient (20°C) and operating temperature (30°C). The model developed in this thesis can be used to examine solutions minimizing temperature fluctuations in such scenarios, but how these techniques would work in reality is left out for future investigation.

Appendix A

Physical constants

Constant Name	Symbol	=	Constant Value (with units)
Heat capacity water	$C_{p,w}$	=	$4184 \text{ J/kg} \cdot \text{K}$
Heat capacity copper	$C_{p,cu}$	=	$386 \text{ J/kg} \cdot \text{K}$
Heat transfer coefficient AS	h	=	$11 \text{ W/m}^2 \cdot \text{K}$
Mass density copper	ρ	=	8960 kg/m^3
Thermal conductivity copper	k	=	$401 \text{ W/m} \cdot \text{K}$
Component surface	A_{cu}	=	0.1 m^2
Mass of component	m	=	16 kg
Ambient temperature	T_∞	=	20°C
Initial temperature	$T_w(0)$	=	28°C

Appendix B

Mathematica notebook

Author: Sara Aasly
sara.hegdahl.aasly@cern.ch
Title: Transient_response_AS
Date: 26/10/2016
Note: remove semicolon ; to show graphs/tables

```
SetOptions[ListLinePlot, Frame → True, Axes → False,  
  LabelStyle → {FontFamily → "Times New Roman", FontSize → 12}, ImageSize → 250];  
SetOptions[Plot, Frame → True, Axes → False,  
  LabelStyle → {FontFamily → "Times New Roman", FontSize → 12}, ImageSize → 250];
```

Transient response for AS

Import raw data from file

Read all rows from column 3 =>[[All, 3]], skip 1 header line

```
path = "\\cern.ch\\dfs\\Users\\s\\saasly\\Documents\\TransientResponse\\Sara\\newDoglegData/";  
file = "log_20160914-16h.csv";  
samplingTime = 2; (* sampling time = 2 sec for Dog-leg .tdms files *)  
filename = path <> file;  
  
tempInRaw = Import[filename, "CSV", "HeaderLines" → 1][[All, 4]];  
tempMidRaw = Import[filename, "CSV", "HeaderLines" → 1][[All, 5]];  
tempOutRaw = Import[filename, "CSV", "HeaderLines" → 1][[All, 3]];  
INCmax = Import[filename, "CSV", "HeaderLines" → 1][[All, 7]];  
TRAmass = Import[filename, "CSV", "HeaderLines" → 1][[All, 8]];  
pulseLength = Import[filename, "CSV", "HeaderLines" → 1][[All, 2]];
```

Constants

```
cpw = 4184; (* Heat capacity water - J/Kg/K *)  
cpcu = 386; (* Heat capacity cupper - J/Kg/K *)  
h = 11; (* Heat transfer coefficient - W/m2/°C *)  
sas = 0.1; (* Component surface - m2 *)  
mas = 16; (* mass of component - Kg *)  
  
tamb = 20; (* Ambient temperature - °C*)  
mwas = 0.026; (* Water flow konstant - Kg/s *)  
t0as = Mean[tempInRaw] (* initial temperature/ In temp - °C*);
```

```

aas = mas * cpcu;
bas = mwas * cpw;
cas = h * sas;
das = bas + cas;
kas = -bas * t0as - cas * tamb;
length = Length[INCmax];
signalLength = Length[INCmax] * samplingTime;

```

Raw data

Convert from RF-power pulses to average power dissipated as heat.

Add time variable to data. Here data is recorded with sampling time of 2 seconds. Sampling time can be changed under constants.

```

powerInRaw = 
$$\frac{(\text{INCmax} - \text{TRAmx}) * \text{pulseLength}}{0.02};$$

powerIn = Table[{samplingTime * x, powerInRaw[[x]]}, {x, 1, length}];
ListLinePlot[powerInRaw, PlotLabel → "Dissipated power signal",
  PlotRange → All, FrameLabel → {"sample nr", "Power / W"}];

```

Create analytical function from the raw data points

Interpolate the data in order to create a function for Mathematica

Then create an analytical function from the interpolated one that is defined from -infinity to +infinity using the Heaviside π function

```

fInterPower = Interpolation[powerIn]

```

InterpolatingFunction[ Domain: {{2., 2.73 × 10⁴}}
Output: scalar]

```

newFpower[x_] := fInterPower[x] HeavisidePi[
$$\left( \frac{\frac{x}{\text{samplingTime}} - \frac{\text{length}}{2}}{\text{length}} \right)$$
]

```

Solve $y(x)' + Dy(x) + K = \underline{P(x)}$

Solve numerically the nHDE => here the forcing term is the function created from the input power data $P(x)$

The domain is set from 0 to signalLength seconds and initial condition as $y[x=0] = t0as$ (the

water in temperature at $t = 0$)

```
solutionNum = NDSolve[
  {aas * y'[x] + das * y[x] + kas == newFpower[x], y[0] == t0as}, y[x], {x, 0, signalLength}];
```

Plot the numerically solution obtained above

```
model = Plot[Evaluate[(((y[x]) /. solutionNum))],
  {x, 0, signalLength}, PlotRange → {{0, signalLength}, {All, All}},
  FrameLabel → {"time / s", "temperature / °C"},
  PlotStyle → ColorData[2, "ColorList"], PlotLegends → {"Model"}];
```

Temperature response

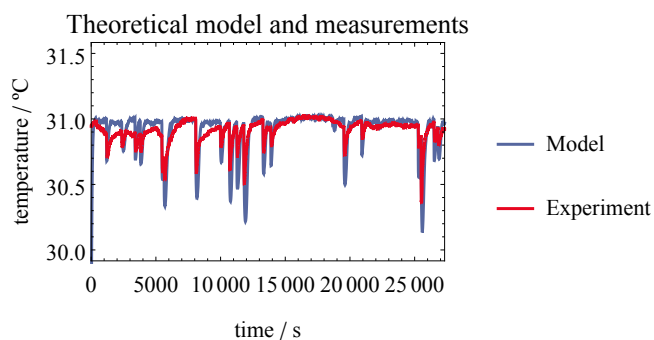
```
temp = tempMidRaw - tempInRaw + t0as;
tempfiltered = Table[{samplingTime * x, temp[[x]]}, {x, 1, length}];
tempPlot = ListLinePlot[tempfiltered, PlotRange → All,
  FrameLabel → {"time / s", "temperature / °C"}, PlotStyle → ColorData[3, "ColorList"],
  FillingStyle → White, PlotLegends → {"Experiment"}];
```

Plots of temperature data from file

```
allTemperatures = ListLinePlot[{tempOutRaw, tempMidRaw, tempInRaw},
  PlotRange → All, PlotLabel → "Raw temperature measurements",
  FrameLabel → {"time / sec", "temperature / °C"},
  PlotLegends → {"Out temperature", "Component temperature", "Input temperature"}];
```

Plot model vs experiment

```
Show[{model, tempPlot}, PlotRange → {{0, signalLength}, {30, 31.5}},
  PlotLabel → "Theoretical model and measurements"]
```



Bibliography

- [1] M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Schulte, and N. Toge. A multi-teV linear collider based on clic technology. Clic conceptual design report, CERN, 2012.
- [2] E. Daskalaki, S. Döbert, M. Duquenne, H. Mainaud Durand, V. Rude, and A. Vamvakas. Study of the Dynamic Response of CLIC Accelerating Structures. (CERN-ACC-2015-286), 2015. URL <https://cds.cern.ch/record/2141828>.
- [3] P. Lebrun, L. Linssen, A. Lucaci-Timoce, D. Schulte, F. Simon, S. Stapnes, N. Toge, H. Weerts, and J. Wells. The clic programme: towards a staged e+e- linear collider exploring the terascale, clic conceptual design report. Technical report, CERN, 2012.
- [4] About CERN. Jan 2012. Accessed in September 2016. URL <http://cds.cern.ch/record/1997225>.
- [5] Member states. 2012. Accessed in November 2016. URL <http://cds.cern.ch/record/1997223>.
- [6] The accelerator complex. Jan 2012. Accessed in December 2016. URL <http://cds.cern.ch/record/1997193>.
- [7] The Large Hadron Collider. Jan 2014. Accessed in September 2016. URL <http://cds.cern.ch/record/1998498>.
- [8] The Higgs boson. Jan 2014. Accessed in December 2016. URL <http://cds.cern.ch/record/1998491>.
- [9] The Nobel Museum. Peter Higgs - Facts. May 2013. Accessed in December 2016. URL <http://cds.cern.ch/record/1998007>.

- [10] The Compact Linear Collider. Jan 2012. Accessed in November 2016. URL <https://cds.cern.ch/record/1997192>.
- [11] CLICdp. April 2014. Accessed in November 2016. URL <http://cds.cern.ch/record/1998665>.
- [12] W. Herr and B. Muratori. Concept of luminosity. CERN, 2009.
- [13] S. Döbert. Clic module & impact of pacman on its alignment. PACMAN workshop, 2017.
- [14] G. Geschonke and A. Ghigo. CTF3 Design Report. Technical Report CERN-PS-2002-008-RF. CTF-3-NOTE-2002-047. LNF-2002-008-IR, CERN, Geneva, May 2002. URL <http://cds.cern.ch/record/559331>.
- [15] CTF3 general description. Accessed in December 2016. URL <http://clic-study.web.cern.ch/content/ctf3-general-description>.
- [16] A. Moilanen. Creep effects in diffusion bonding of oxygen- free copper. Master's thesis, Aalto University, April 2013.
- [17] Z. Insepov, J. Norem, D. Huang, S. Mahalingam, and S. Veitzer. Modeling rf breakdown arcs. 2010.
- [18] A. Descoeudres, Y. Levinsen, S. Calatroni, M. Taborelli, and W. Wuensch. Investigation of the dc vacuum breakdown mechanism. physical review special topics-accelerators and beams. vol. 12.9, no. 9, pp. 092001, CERN, 2009.
- [19] B. J. Woolley. *High Power X-band RF Test Stand Development and High Power Testing of the CLIC Crab Cavity*. PhD thesis, Lancaster University, 2015. Cited on page 5.
- [20] Y. A. Cengel. *Heat and Mass Transfer, a practical Approach*. McGraw-Hill, 2 edition, 2003. ISBN 0-07-245893-3 / 0.07-115150-8(ISE). Cited on pages 9-17, 26, and 210-213.
- [21] A.K. Saxena and C.M Tiwari. *Heat and Thermodynamics*, volume 1. Alpha Science, 1 edition, 2014. ISBN 978-1-84265-902-1. Cited on page 1.27.
- [22] K. V Wong. *Thermodynamics for Engineers, Second Edition*. Boca Raton: CRC Press, 2 edition, 2012. ISBN 9781439845592.

-
- [23] T.L. Bergman, A.S. Lavine, F.P. Incropera, and D.P. Dewitt. *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons Incorporated, 2010. ISBN 9780470945377. Cited on page 283.
- [24] Béla G. Lipták. *Instrument Engineers' Handbook: Process control and optimization*, volume 2. CRC Press, 4 edition, 2003. ISBN 0-8493-1081-4.
- [25] Wolfram Language & System, Documentation Center, NDSolve. Accessed in December 2016. URL <http://reference.wolfram.com/language/ref/NDSolve.html>.