PCCE - A Predictive Code for Calorimetric Estimates in actively cooled components affected by pulsed power loads

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Abstract

The analytical interpretative models for calorimetric measurements currently available in the literature can consider close systems in steady-state and transient conditions, or open systems but only in steady-state conditions.

The PCCE code (Predictive Code for Calorimetric Estimations), here presented, introduces some novelties. In fact, it can simulate with an analytical approach both the heated component and the cooling circuit, evaluating the heat fluxes due to conductive and convective processes both in steady-state and transient conditions.

The main goal of this code is to model heating and cooling processes in actively cooled components of fusion experiments affected by high pulsed power loads, that are not easily analyzed with purely numerical approaches (like Finite Element Method or Computational Fluid Dynamics). A dedicated mathematical formulation, based on concentrated parameters, has been developed and is here described in detail.

After a comparison and benchmark with the ANSYS® commercial code, the PCCE code is applied to predict the calorimetric parameters in simple scenarios of the SPIDER experiment.

Keywords: predictive, code, calorimetry, estimates, cooling

Introduction

During operations of fusion experiments, some components can be affected by high heat fluxes, that can lead to local damages and component burnout if the heat load is not exhausted by a proper cooling system. Among these high heat flux components, there are some parts of the Neutral Beam Injectors (Radio Frequency drivers, acceleration grids, beam line components), of the Radio Frequency antennas, of the Divertor and of the Blanket.

Measuring the temperature and thermal energy can be useful for the design of such components, and to have information on the energy fluxes inside the machines for monitoring and protecting them during operations [1, 2]. In particular, measuring the energy absorbed by these components during short pulses can be useful before operating the experiment with long pulses, which are much more critical in terms of risks of damage.

A simplified scheme of a generic actively cooled component subject to an externally applied power load is shown in Fig. 1. A certain mass flow $\dot{m}$ of coolant (water most of times) exhausts most of the heat absorbed by the component, being the remaining part exhausted by thermal conduction and radiation processes. As the components are generally inside a vacuum environment, convection processes with the surrounding fluid are not considered in this analysis.

Calorimetric measurements can be carried out both in continuous working conditions and during pulsed power sessions. In the first case, a steady state condition is generally reached after a proper time interval and the following power balance formula

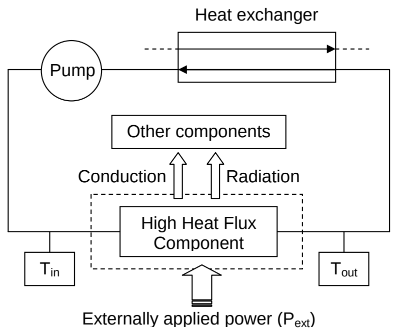

Figure 1: Cooling scheme of a generic high heat flux component.

can be used to estimate the power absorbed by the component [3]:

$$P = \rho \cdot \dot{V} \cdot C_{fluid} \cdot (T_{out} - T_{in}) \tag{1}$$

where ρ is the coolant density, $\dot{V}$ is coolant volume flow, C_{fluid} is the coolant specific heat capacity (at constant pressure), T_{in} is the coolant inlet temperature and T_{out} is the coolant outlet temperature.

$\dot{V}$, T_{in} and T_{out} can usually be measured with flux meters and thermocouples respectively, while the thermo-physical properties ρ and C_{fluid} are known functions of the coolant temperature.

In pulsed power sessions, there could be not enough time to reach a steady state condition, so it might be not possible to measure a value of T_{out} that is stable for a sufficient time. In this case, Eq. (1) cannot be used for the calorimetric estimates, and more sophisticated mathematical tools must be adopted for

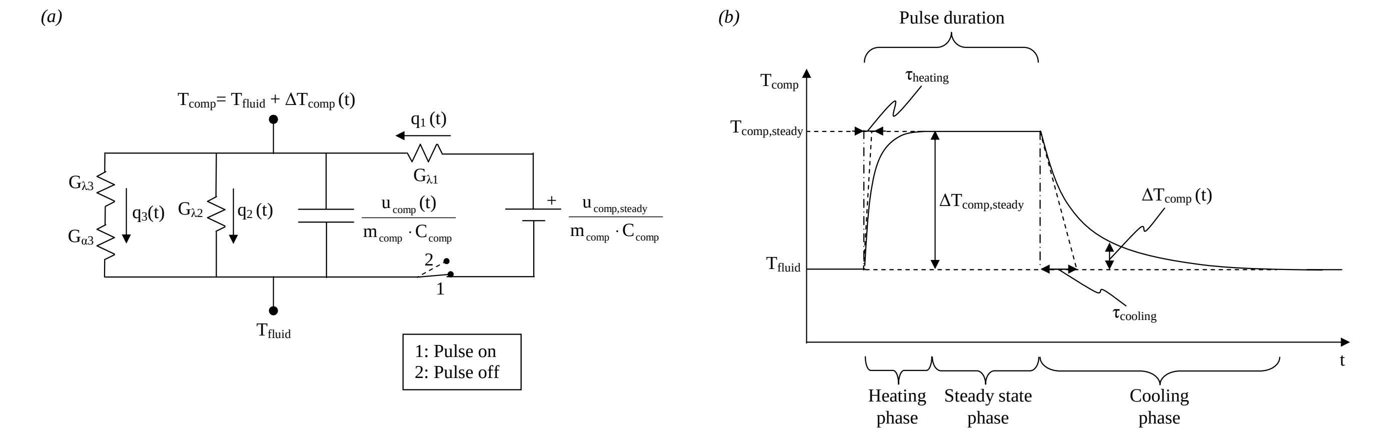

Figure 2: Simplified model of heat exchange inside an actively cooled component: (a) Equivalent electrical scheme; (b) Time behaviour of component average temperature.

the system modeling.

These tools can be used for the interpretation of experimental measurements in order to obtain evaluation of the absorbed heat loads [4], or to predict the behaviour of a component affected by pulsed power loads and actively cooled by means of a dedicated cooling system. Regarding the latter point, the PCCE code (Predictive Code for Calorimetric Estimates)[1] is here presented and described in detail. This code treats the above presented problem following a non-linear analytical concentrated parameters model, with a numerical routine to adjust the material and coolant properties as functions of their respective temperature. It can consider (under some simplifying hypotheses) all the main factors playing a role in the heating and cooling processes, and has the advantages to be easier to handle than the commercial numerical models (in PCCE there are no mesh to be generated and the heat exchange models are rather straightforward) and to run faster (analyses only take few seconds).

1. A simplified model of the heating and cooling processes of an active cooled component

Fig. 2 shows a simplified model of the heating and cooling processes of an actively cooled high heat flux component. The aim of this model is to find a relationship between the parameters that play a role in the heating and cooling processes, particularly during transient conditions. Among these parameters, the most important, taken into account by the model, are the component mass and geometry, the material and coolant thermo-physical properties (density, heat conductivity, specific heat capacity), the applied heating power, the pulse length, the coolant flow rate, the time needed to reach a steady state conditions after the heating phase and the time for a complete cooling of the component after the pulse.

In order to better understand the relationship between all these parameters, it is useful to consider an equivalent electric scheme, as shown in Fig. 2a. A direct correspondence can be identified between thermal and electrical quantities. Namely, voltage corresponds to temperature, electric current to heat flow, electrical conductance to thermal conductance (where heat exchange processes can occur by means of thermal conduction or convection), an electrical capacitor to a thermal capacity (given by a body that can accumulate thermal energy) and a voltage generator to a heating power load. A switch is also considered in the equivalent model whose possible positions are pulse on (position 1) and pulse off (position 2).

2. Estimation of the thermal conductances

Three phases can be distinguished during pulsed power operations: a heating phase (when the externally applied thermal load P_{ext} heats the component), a steady-state phase (when a thermal equilibrium is reached and P_{ext} is completely transferred to the coolant and to the mechanical supports) and a cooling phase (when P_{ext} is switched off and the thermal energy is exhausted by the coolant and by the mechanical supports until a new equilibrium state is reached).

During these phases, the following thermal conductances play a role:

- $G_{\lambda 1} = \frac{\lambda_{comp} \cdot A_{\lambda 1}}{s_{\lambda 1}}$, conductance inside the component body during the heating phase;
- $G_{\lambda 2} = \frac{\lambda_{support} \cdot A_{\lambda 2}}{s_{\lambda 2}}$, conductance corresponding to the heat exchanged by conduction between the considered component and its mechanical supports;
- $G_{\lambda 3} = \frac{\lambda_{comp} \cdot A_{\lambda 3}}{s_{\lambda 3}}$, conductance inside the component body during the cooling phase;
- $G_{\alpha 3} = \alpha \cdot A_{\alpha} = 0.027 \cdot Re^{0.8} \cdot Pr^{\frac{1}{3}} \cdot \frac{\lambda_{fluid}}{D_h} \cdot A_{\alpha}$, conductance corresponding to the heat exchanged by thermal convection between the component and the coolant.

λ_{comp} is the thermal conductivity of the component, $\lambda_{support}$ the thermal conductivity of the mechanical support material,

[1] A copy of the PCCE code is available on demand.

$A_{\lambda i}$ and $s_{\lambda i}$ the section areas and thicknesses of the connections (i can be 1,2 or 3), α the convective heat transfer coefficient, calculated in this case with the Sieder-Tate formula [5], A_α the heat exchange area for convection (the interface area between component and coolant), $Re = \frac{v \cdot D_h}{\nu}$ the Reynolds number, $Pr = \frac{C_{fluid} \cdot \mu}{\lambda_{fluid}}$ the Prandtl number, v the coolant velocity inside the cooling channel, D_h the hydraulic diameter of the channel, ν the cinematic fluid viscosity, C_{fluid} the fluid specific heat capacity, μ the fluid dynamic viscosity and λ_{fluid} the thermal conductivity of the cooling fluid.

As the operating temperature of the actively cooled components for fusion experiments must be controlled under suitable levels (depending on the material and coolant), the heat flux by thermal radiation is generally much smaller than the ones by convection and conduction (see for example [4]), and hence it is here neglected.

3. Estimation of the component temperature as a function of time

In order to investigate the component heating and cooling processes, let us consider the equivalent electric scheme in Fig. 2a. Passing from the "pulse off" to the "pulse on" condition (this corresponds to a pulse initiation), the component is subject to a heating phase (when the temperature rises) until it reaches a steady state condition (when the temperature becomes stable).

3.1. Steady state condition

The composition of $G_{\lambda 2}$, $G_{\lambda 3}$ and $G_{\alpha 3}$ represents the thermal conductance to be considered for cooling, and can be calculated as:

$$G_{eqv,cooling} = G_{\lambda 2} + \frac{G_{\alpha 3} \cdot G_{\lambda 3}}{G_{\alpha 3} + G_{\lambda 3}} \quad (2)$$

In fact, the total conductance can be estimated as the series of $G_{\lambda 3}$ and $G_{\alpha 3}$, in parallel with $G_{\lambda 2}$. In steady state conditions, an equilibrium is found when the condition $\Delta T_{comp,steady} = \frac{P_{ext}}{G_{eqv,cooling}}$ is reached. Hence, the component steady state temperature can be estimated as:

$$T_{comp,steady} = T_{fluid} + \Delta T_{comp,steady} = \frac{T_{in} + T_{out,steady}}{2} + \frac{P_{ext}}{G_{eqv,cooling}} \quad (3)$$

where T_{fluid} is estimated as the average temperature between the inlet coolant temperature T_{in} and the outlet coolant temperature in steady state conditions $T_{out,steady}$.

3.2. Heating phase

During the heating phase, the heat fluxes from the component to the surrounding bodies $q_2(t)$ and to the coolant $q_3(t)$ are usually much smaller than the heat flux $q_1(t)$ due to the externally applied power load, and so they can be considered negligible. Hence, the system can be described by the following equation:

$$\frac{u_{comp,steady}}{m_{comp} \cdot C_{comp}} - \frac{1}{G_{\lambda 1}} \cdot q_1(t) - \frac{u_{comp}(t)}{m_{comp} \cdot C_{comp}} = 0 \quad (4)$$

where m_{comp} is the component mass, C_{comp} the specific heat capacity of the component material, $u_{comp}(t)$ the thermal energy accumulated in the component at a generic instant, $\Delta T_{comp}(t) = \frac{u_{comp}(t)}{m_{comp} \cdot C_{comp}}$ the component temperature increase (difference between the component average temperature T_{comp} and the average fluid temperature T_{fluid}) at a generic instant, and $u_{comp,steady}$ the thermal energy accumulated in the component when the steady state condition is reached.

$q_1(t)$ can be written as $\frac{du(t)}{dt}$ and so Eq. (4) becomes:

$$\frac{u_{comp,steady}}{m_{comp} \cdot C_{comp}} - \frac{1}{G_{\lambda 1}} \cdot \frac{du_{comp}(t)}{dt} - \frac{u_{comp}(t)}{m_{comp} \cdot C_{comp}} = 0 \quad (5)$$

As a result of this differential equation, the energy stored in the component due to the heating process (corresponding to the capacitor charge in the electrical equivalence) can be described as a function of time, as represented in Fig. 2b:

$$u(t) = u_{comp,steady} \cdot (1 - e^{-\frac{t}{\tau_{heating}}}) \quad , \tau_{heating} = \frac{m_{comp} \cdot C_{comp}}{G_{\lambda 1}} \quad (6)$$

It can be considered that after a pulse-on time equal to $\tau_{heating}$ (heating time constant), $\Delta T_{comp}(t) \cong 0.63 \cdot \Delta T_{comp,steady}$. Practically, the heating phase can be considered to last $5 \cdot \tau_{heating}$. In fact, after such a heating time, being $\Delta T_{comp}(t) \cong 0.99 \cdot \Delta, T_{comp,steady}$, the heating phase can be considered accomplished. A graphical representation of $\tau_{heating}$ is shown in Fig. 2b.

3.3. Cooling phase

Passing from the "pulse on" to the "pulse off" condition, the component is subject to a cooling phase, after which a steady state condition of complete cooling is reached. In this case, the system can be described by the equation:

$$\frac{u_{comp}(t)}{m_{comp} \cdot C_{comp}} - \frac{q_2(t) + q_3(t)}{G_{eqv,cooling}} = 0 \quad (7)$$

where $q_2(t)$ is the heat exhausted by thermal conduction to the mechanical supports and $q_3(t)$ is the heat exhausted by thermal convection to the coolant.

The total heat exhausted $q_2(t) + q_3(t)$ can be written in this case as $\frac{du(t)}{dt}$, and the thermal energy stored in the component during the cooling process can be written as:

$$u(t) = u_{comp,steady} \cdot e^{-\frac{t}{\tau_{cooling}}} \quad , \tau_{cooling} = \frac{m_{comp} \cdot C_{comp}}{G_{eqv,cooling}} \quad (8)$$

A graphical representation of $\tau_{cooling}$ is shown in Fig. 2b.

4. Estimation of the coolant outlet temperature as a function of time

In the hypotheses of no heat losses along the cooling manifolds and neglecting the time delay due to the water velocity in the manifolds, the coolant outlet temperature can be written as:

$$T_{out}(t) = T_{in}(t) + \frac{q_3(t)}{\rho \cdot \dot{V} \cdot C_{fluid}} \quad (9)$$

Table 1: Estimation with PCCE of the main parameters of the heating and cooling processes in the SPIDER experiment. (FSBP: Faraday Shield Back Plate; FSLW: Faraday Shield Lateral Wall; RFC: Radio Frequency Coils; DP: Drivers plate; LW: Lateral Wall; BP: Bias Plate; PG: Plasma Grid; EG: Extraction Grid; GG: Grounded Grid; ED: Electron Dump)

	FSBP	FSLW	RFC	DP	LW	BP	PG	EG	GG	ED
Material	Cu	Cu	Cu	Cu	Cu+SS	Cu	Cu	Cu	Cu	Cu
$m_{comp}[kg]$	17	34	13	98	45	3	101	124	141	80
$\dot{m}[kg/s]$	2.1	5.4	0.6	3.2	2.1	0.6	0.6	11.6	8.4	32.6
$P_{ext}[kW]$	73	480	25	160	100	10	20	1000	700	1000
$G_{\lambda 1}[kW/°C]$	20	12	441	200	78	37	89	73	66	67
$G_{\lambda 2}[kW/°C]$	0.002	0.002	0.008	0.001	0.001	0.002	0.002	0.002	0.002	0.001
$G_{\lambda 3}[kW/°C]$	39	36	441	100	156	75	201	267	267	1131
$G_{\alpha 3}[kW/°C]$	41	42	29	7	19	38	11	47	22	227
$G_{eqv,cooling}[kW/°C]$	20	19	27	6	17	25	10	46	22	227
$T_{in}[°C]$	35	35	35	35	35	150	150	35	35	35
$T_{out,steady}[°C]$	43	56	45	47	46	153	158	56	55	42
$T_{comp,steady}[°C]$	42	70	41	66	46	152	156	66	76	43
$\tau_{heating}[s]$	0.33	1.07	0.01	0.19	0.27	0.02	0.44	0.66	0.81	0.03
$\tau_{cooling}[s]$	0.33	0.67	0.19	5.88	1.22	0.04	3.76	1.03	2.45	0.14

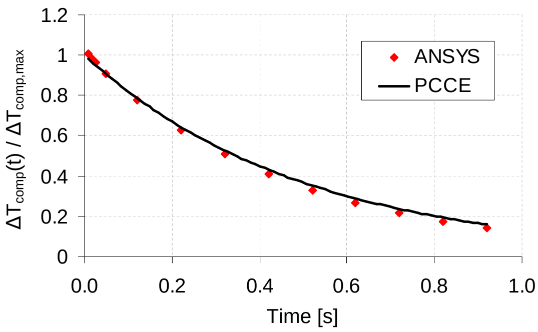

Figure 3: Benchmark of PCCE against ANSYS® (transient analysis with a tridimensional finite element model). ΔT_{comp} is equal to the difference between T_{comp} and T_{fluid}. A good agreement can be observed between the two codes.

During the steady state phase, $q_2(t) + q_3(t)$ is constant and equal to the heating power P_{ext}. Following the equivalent electrical scheme, P_{ext} can be written as function of $q_3(t)$:

$$P_{ext} = q_2(t) + q_3(t) = q_3(t) \cdot \frac{G_{eqv,cooling}}{\frac{G_{\alpha 3}+G_{\lambda 3}}{G_{\alpha 3} \cdot G_{\lambda 3}}} = q_3(t) \cdot k \qquad (10)$$

where k depends on the thermal conductances.

Hence, Eq. (9) can be written as:

$$T_{out,steady} = T_{in} + \frac{P_{ext}}{\rho \cdot \dot{V} \cdot C_{fluid} \cdot k} \qquad (11)$$

that gives the outlet coolant temperature as function of the applied power and cooling parameters.

5. Benchmark of PCCE and application to the SPIDER experiment

The formulae reported in the previous paragraphs have been implemented in the PCCE code, developed in VISUAL BASIC® environment. Comparing the PCCE results with those obtained from a transient analysis with a tridimensional finite element thermo-mechanical model in ANSYS® [6], a good agreement has been observed, as visible from Fig. 3.

The PCCE code have been then applied to calculate the cooling parameters of the principal actively cooled components of the SPIDER experiment [7, 8]. The results, reported in Tab. 1, have been used for the design of the SPIDER cooling plant [9].

Conclusions

A non-linear analytical model (iteratively updated with a numerical routine) has been developed for the investigation of heating and cooling processes in fusion experiments, and implemented into the PCCE code (Predictive Code for Calorimetric Estimates). The main advantages of PCCE are an easier usage and a faster run time than the commercial numerical models. PCCE have been benchmarked against ANSYS® with good agreement and applied to evaluate the performances of the cooling systems for high heat flux components in the SPIDER experiment.

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