SPALLATION NEUTRON SOURCE DRIFT TUBE LINAC RESONANCE CONTROL COOLING SYSTEM MODELING*

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Abstract

The Resonance Control Cooling System (RCCS) was designed by Los Alamos National Laboratory for the warm linac of the Spallation Neutron Source. The primary design focus was directed on water-cooling of individual component contributions. The sizing of the RCCS water skid was accomplished by means of a specially created SINDA/FLUINT model tailored to these system requirements. A new model was developed in Matlab Simulink and incorporates actual operational values and control valve interactions. The model took into consideration the dependence of RF input power on cavity detuning values during transients, time delays that resulted from water flows through the heat exchanger, the dynamic process of water warm-up in the cooling system due to dissipated RF power on the cavity surface, differing contributions on the cavity detuning due to drift tube and wall heating, and a dynamic model of the heat exchanger with characteristics, which were in close agreement to the real unit. Because of the Matlab Simulink model, investigation of a wide range of operating issues during both transient and steady state operation is now possible. Some results of the DTL RCCS modeling are presented.

INTRODUCTION

To understand the model which has been developed it is important to first examine the main blocks or subsections from which it was built.

- *RF POWER;* represents the dependence of dissipated RF power on the cavity detuning.
- *WALL* and *DRIFT TUBE;* are used to determine the processes of cavity heating by RF losses separately in the cavity walls and in the drift tubes.
- *COOLING;* takes into account the process of water heating in the cooling system channels.
- *HEAT EXCHANGER;* supplies the heat transfer values from the cooling system to the facility cold water with parameters very close to the actual unit.
- *Control Valve CV-1;* determines variable time delays in the heat exchanger and water flow by-pass as a function of controlled variables. It regulates the water flows through the by-pass and heat exchanger;
- *MOTOR;* controls the 3-way mixing valve.

The system also contains a *HEATER* which could be used for preliminary warming of the cavity. A better description of each block, the feedback circuits used, and modeling results with conclusions will be presented.

BLOCK DESCRIPTIONS

RF POWER

This block allows two modes of operation – temperature mode (TM) where the cavity resonance frequency is followed by the low level RF (LLRF) frequency; and frequency mode (FM) where the LLRF frequency is stable. In the latter case the value of RF power $P_{RF}(t)$ dissipated on the cavity surface is expressed by:

$$P_{RF}(t) = \frac{Po}{1 + (2Q_n \frac{(df)_p(t) - (df)o}{f_o})^2} \quad (1)$$

Where Q_n is the loaded cavity quality factor, Po is the average RF power dissipated in a tuned cavity, $(df)_0 > 0$ is an initial deviation in tank frequency from the LLRF frequency, and $(df)_p(t)$ is the tank frequency detuning due to tank heating by RF losses. In turn, it is supposed that $(df)_0 = (T_o - T_{in})S_o$, where T_0 is the so-called tank metal resonance temperature, corresponding to the cavity resonance frequency 402.5 MHz (it used to be equal 25^0C). T_{in} is the initial tank temperature. $S_o = S_w + S_d$ is a sensitivity of the tank resonance frequency to the cooling water temperature. S_w and S_d are sensitivities of tank resonance frequency to wall and drift tube temperatures respectively.

The RF Power block, in FM operation, describes the so-called self-regulating circuit, which is a consequence of the cavity with high quality factor. This circuit creates additional negative feedback during overheating of the tank and positive feedback during underheating.

WALL AND DRIFT TUBES

These two blocks are described by means of the well-known [1] differential equation (DE):

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$$C_m M_m \frac{dT_m}{dt} = P_m + (hA)_m \left(\frac{T_{hi} + T_h}{2} - T_m\right), \qquad (2)$$

where T_m - metal temperature, $(hA)_m$ - product of the metal (steel for the walls and copper for drift tubes) heat transfer coefficient (h), and heat exchange square in cooling channels (A). $C_m M_m$ – is the product of the metal specific heat and metal mass. DE (2) determines the process of tank metal heating by RF power P_m, dissipated in walls ($P_m = P_w = k_w P_o$) or drift tubes ($P_m = P_d = k_d P_o$), relatively of the average water temperature T_{ha}:

$$T_{ha} = \frac{T_{hi} + T_h}{2}. \qquad (3)$$

Here T_{hi} and T_h are temperatures of water at the output and input of the cavity cooling channels. As well, these values are used (via time delays) for the water temperatures at the input and output of the heat exchanger. In turn, the total change of metal temperature $dT_m = T_m - T_0$ in relation to the resonance temperature To corresponds to the cavity detuning value separately for the walls $(df)_w = S_w(T_o - T_{mw})$ and for the drift tubes $(df)_d = S_d(T_o - T_{md})$.

COOLING

When deriving the differential equation describing the process of water heating, the following conditions were taken into account.

- Water in the cooling system during transients is heated up by power deposited through the metal of the drift tubes and walls. As follows from (2), the value of this power may be presented as:

$$P_{wat} = (hA)_d (T_{md} - T_{ha}) + (hA)_w (T_{mw} - T_{ha}). \qquad (4)$$

- The cooling system is a closed one.

Taking into account expression (4) and the dependence water temperature on the water mass in the cavity cooling channels, one can get the next differential equation:

$$C_w M_w \frac{dT_{hi}}{dt} = (hA)_w (T_{mw} - T_{ha}) + (hA)_d (T_{md} - T_{ha}) + C_w F_0 (T_h - T_{hi}). \qquad (5)$$

Here C_w is the waters specific heat, M_w – mass of water in the cavity cooling channels, F_0 – water pump flow rate.

HEAT EXCHANGER

Processes in the heat exchanger (HE) are described by the next system of differential equations:

$$\begin{aligned} C_w M_h \frac{dT_{ho}}{dt} &= (UA)_{ov}(T2 - T1) + C_w F_h (T_{hi} - T_{ho}) \\ C_w M_c \frac{dT_{co}}{dt} &= (UA)_{ov}(T1 - T2) + C_w F_c (T_{ci} - T_{co}) \end{aligned} \qquad (6)$$

In expression (6) $T1 = \frac{1}{2}(T_{hi} + T_{ho})$, $T2 = \frac{1}{2}(T_{ci} + T_{co})$, F_c and F_h are flow rates of cold and hot water. T_{ci} is a "cold" water temperature at the HE input, T_{co} is a cold water temperature at the HE output, T_{ho} is a "hot" water temperature at the HE output, and M_h and M_c are masses of water inside the hot and cold water channels of the HE.

$$(AU)_{ov} = A \frac{U_1 U_2}{U_1 + U_2} \qquad (7)$$

Here $U_1 = K_1 (F_h)^{0.8}$ is a heat transfer coefficient for the hot water into the thin metal wall between the hot and cold waters. $U_2 = K_2 (F_c)^{0.8}$ is a heat transfer coefficient for the metal wall into the cold water. A is the square of the heat exchange surface. Coefficients K_1 and K_2 in expression (7) are selected to provide the best coincidence of the dependence of $(AU)_{OV}$ on F_h and F_c with that of the real heat exchanger, presented in [1].

Control Valve CV-1

This block represents the peculiarities of the 3-way control valve operation. It divides a flow with flow rate F_o*(kg/sec)* and temperature T_{hi} between the heat exchanger (F_h) and the by-pass ($F_0 - F_h$). After cooling a portion of the water in the heat exchanger it all mixes again with temperatures T_{hi} (at the by-pass output) and T_{ho} (at the heat exchanger output). The resulting temperature, T_{out}, is determined as:

$$T_{out} = T_{hi}(1 - F_h F_o^{-1}) e^{-st_1} + T_{ho} F_h F_o^{-1} e^{-st_2}.$$

Where $t_1 = M_b / (F_o - F_h)$, sec and $t_2 = M_h / F_h$, sec are variable time delays and M_b and M_h are the masses of water in the by-pass and heat exchanger lines (kg).

MOTOR

The model of the block MOTOR was created taking into account real parameters of the proportional controller, *Electro-hydraulic Actuator Type 3274 –13*, of the 3-way, CV-1, valve. During testing a backlash was discovered in the actuator for small values of hot water flow F_h, not exceeding 10% from maximum value. Then, it was observed that the step response of the actuator was typical for the DAC at the output of the actuator.

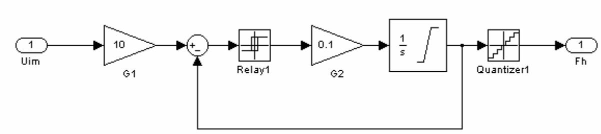

Figure 1: The model of block MOTOR.

The continuous model of the block MOTOR, realizing all above-mentioned peculiarities of the actuator, is shown in fig.1. The gains of Simulink blocks *G1* and *G2* were chosen to achieve the maximum flow rate of "hot" water F_h = 15 kg/sec in ~120 sec after the stepwise input signal appearance. The quantization interval in the Simulink block *Quantizer 1* was determined taking into account a number of steps of the real control characteristics. The resulting control characteristics of the block *MOTOR* are in a good agreement with the experimental ones.

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FEEDBACK CIRCUITS

In addition to the blocks described above there are a few Simulink blocks in the Model feedback circuit, namely, two separate *PID controllers*, one for temperature and the other for frequency mode of operation, and two *Sum blocks.* The first produces an error signal in TM as a result of comparing temperature T_{hi} and temperature set point T_{sp}. The second block produces the error signal in FM by means of summarizing cavity detuning $(df)_d$ and $(df)_w$. The value of T_{sp} is determined in such a way that the metal temperature of the cavity in TM operation is equal to the metal resonance temperature T_o. At that, it is not difficult to show that the temperature set point T_{sp} can be expressed as:

$$T_{sp} = T_o - \left(\frac{S_d K_d}{(hA)_d} + \frac{S_w K_w}{(hA)_w}\right)\frac{P_o}{S_o} \ . \qquad (8)$$

From (8) it follows that during preliminary warm up of the cavity by means of the block *Heater* $(P_o=0)$ $T_{sp}=T_o$, i.e. temperatures of the water and cavity are the same. With RF power P_o increasing the temperature setup T_{sp} needs to be decreased. In turn, cold water flow rate F_c has to be increased so that the 3-way valve will be controllable after reaching a steady state. Switching between modes of operation can be done in both manually and automatically. Finally, two blocks *Time delays,* one between the main supply manifold of the cavity cooling system and block *CV-1* and another between the return manifold and the block *Heat exchanger,* are included in the cavity cooling system Model.

MODELING RESULTS

RCCS modeling has been carried out for the third cavity of the DTL system. Just this cavity was considered in [1], where all constant numerical values of the Model blocks parameters were determined. Moreover, during modeling it is necessary to keep in mind the values of the *Initial condition* temperature, T_{in}, in the Simulink block *Integrator* as well as the *Initial input* temperature, T_{ii}, in the *Transport Delay* blocks.

The point is that because integration is a more numerically stable operation than differentiation, in Matlab, ordinary differential equations are transformed into ones that use integration operators. It follows then that the number of Simulink *Integrator* block equals the order of the highest derivative. So in every above-mentioned block, described by a first order differential equation, there is one *Integrator* block with initial conditions that depend upon the starting temperature value, T_{in}, before simulation. As a rule, if the preliminary heating is realized by outside sources such as a *Heater* then $T_{in}= T_{ii}$.

As an example, in fig.2 the step responses of RF power P_{RF} (kW), common cavity detuning $(df)_o$-$(df)_p$, cavity output water temperature T_{hi}, and the water flow rate F_h (gpm) through the heat exchanger are shown. Here P_o=90kW, T_{ii}=T_{in}=23.5^{0}C (step input of RF power *Po* took place when the cavity resonance frequency fell within the frequency band ±10kHz), T_o=25^{0}C, F_c=5kg/sec, the chilled water temperature T_{ci}=7^{0}C, in frequency mode of operation. All other values, which are part of expressions (1) - (7), correspond to those, presented in [1] for the third DTL cavity. The dependencies present two processes of interest. First, is a step input of RF power in the preliminary heated cavity. Second, after achieving a steady state operation, is the short-term (for ~60 sec) switching off of RF power. The presented dependencies demonstrate the possibility of the Matlab Simulink Model to easily and quickly provide numerical estimations of transients in the RCCS.

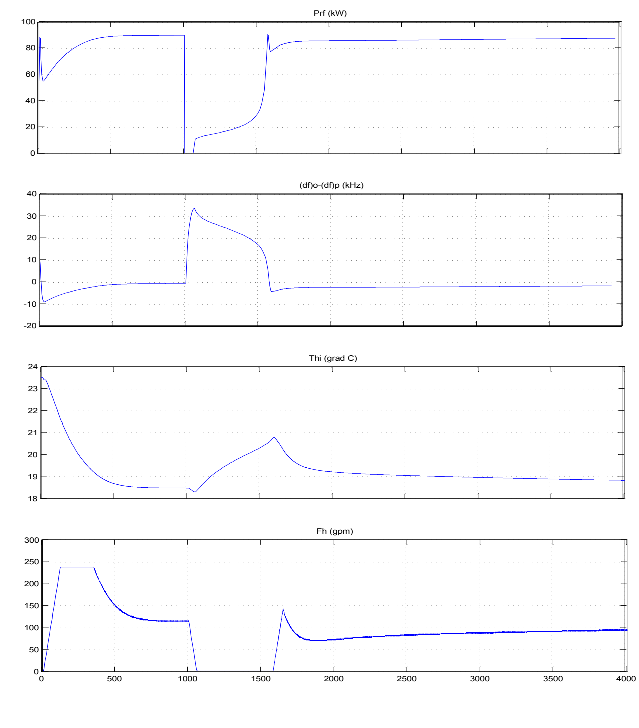

Figure 2: Example of transients in the RCCS DTL Model.

Tests of the Model show that the smaller the value of dissipated RF power, Po, the more difficult it is to reach stable functioning of the control system. Also, it was noticed, that PID parameters have to be carefully chosen every time after changing of the operating conditions.

CONCLUSION

Initial tests of the Model and the comparison of the Model simulation and RCCS operation results show that the Model is very useful for decision of the problem arising during RCCS operation. Using the broad abilities of Matlab the Model is able to check and optimize any operation condition of interest in the RCCS environment.

REFERENCES

[1] Spallation Neutron Source Drift Tube Linac Water Cooling and Resonance Control, FDR (SNS-104020500-DE0001-R00).