DESIGN OF COOLING SYSTEM FOR RESONANCE CONTROL OF THE PEFP DTL*

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Abstract

The temperature-controlled water cooling system has been designed to obtain the resonance frequency stabilization of the normal conducting drift tube linac (DTL) for the PEFP 100 MeV proton linear accelerator. The sizing of individual closed-loop low conductivity cooling water pumping skids for each DTL system is conducted with a simulation of thermo-hydraulic network model. The temperature control schemes incorporating the process dynamic model of heat exchangers is examined to regulate the input water temperatures into the DTL during transient and steady state operation.

INTRODUCTION

The PEFP 100 MeV proton linear accelerator with a maximum duty cycle of 8% and proton beam of 20 mA is being designed as a user facility for scientific and industrial research and development [1]. This is composed of seven modules for beam acceleration from 20 MeV to 100 MeV, and one module for 20 MeV beam acceleration. Each module is made up of three sections, with each section of 2 m long tank housing EQM-contained drift tubes [2]. The RF electrical energy is fed into the DTL cavities to provide a 2.58 MV/m gradient electrical field that serves to accelerate the beam with energy gain of 1.67 MeV/m [3]. While a large amount of an electrical energy is used to accelerate the protons, approximately 70-80% of this electrical energy is dissipated in the DTL drift tubes and tank walls. The dissipated RF power in the DTL cavities results in a considerable cavity detuning.

To maintain the desired resonance frequency keeping it from the cavity detuning, each cavity has to be cooled by cooling water. Furthermore, it has to be heated to a resonance-conditioned temperature before supplying RF power into the cavity, and the temperature of cooling water has to be decreased with RF power supply so that the temperature of cavity body may be unchangeable to sustain the resonance frequency. The resonance control cooling water systems for the DTL cavity with a closed-loop water cooling and temperature control system has been constructed for other linear accelerator system [4,5].

This paper describes the numerical network analysis of the PEFP DTL cooling water system, including the sizing of system components and the PID temperature control scheme through the heat exchanger. And the test results for temperature control in heat exchanger loop by using PEFP 20 MeV cooling water system are also given to assess dynamic features of water cooling process design.

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DESIGN REQUIREMENTS AND WATER PUMPING SKID

Design Requirements

The PEFP DTL water cooling system removes the dissipated heat from the copper RF structures and maintains resonance frequency through the active temperature control. In previous study [2], the drift tube frequency shift (about -5 kHz/°C) is 4 to 6 times more sensitive to water temperature changes than that of tank body. In PEFP DTL resonance cooling system, the cooling water temperature in the drift tubes will be dynamically controlled to maintain the resonance frequency while the tank body is cooled by constantly temperature-controlled utility water. The maximum range of frequency control of ±30 kHz with a reference frequency of 350 MHz, corresponds to an inlet water temperature range ±6 °C about the mean value of 27 °C. To avoid field error and frequency mismatch, the frequency shift needs to be same for all DTL cells. This will be achieved by properly regulating the water flow rate to each drift tube by using an orifice plate upstream of each individual drift tube. Table 1 summarize the design requirements of DTL drift tubes for water cooling system design.

Table 1: Design requirements of DTL drift tubes for water cooling system design

Parameter	Value	Remark
Nominal heat load per drift tube	o 1.53-2.21 kW (for 20 MeV) o 1.22-2.04 kW (for 100 MeV)	Including heat load of 1.5 kW, EQM
Nominal operating temperature	o 27 ^{o}C	Average drift tube operating temp.
Nominal water flow rate per drift tube	o 0.86-1.27 m^3/hr o 0.7-1.18 m^3/hr	Flow rate is adjusted for each drift tube
Flow pressure drop	o 0.3-0.5 kg/cm^2	From the standard pipe estimation
Temperature range of supply water	o ±6 ^{o}C about mean temp.	Resonance control of ±30 kHz
Temperature accuracy/stability	o ±0.5/0.1 ^{o}C	

Water Pumping Skid

The water cooling system configuration for a single DTL system (for the drift tubes) will be consisted of the manifold of RF structures, water pumping skid, transfer pipe lines and a service chilled water line. At current status in PEFP (eleven sets of pumping skids for all DTL's), the DTL water pumping skid is mainly focused on prototype design and fabrication (extreme case of high heat load) to assess the resonance condition by using the 20 MeV proton linac test facility [1,2]. The water pumping skid is a self-contained unit with all of the necessary plumbing, water treatment equipment, instrumentation, pumping and heat transfer hardware required for delivering water at a desired flow rate and temperature to the DTL system. The design objective of this water pumping skid is to size heat exchangers, pumps, control valves and pipe lines that provide the necessary water flow and water temperature to support cooling of each DTL system while maintaining pressure losses and material costs. Table 2 describes the design parameters of heat load as well as water flow rate and temperature requirements of the prototype pumping skid. A flow diagram of water pumping skid is also shown Fig. 1.

Table 2: Design parameters of prototype DTL water pumping skid

Pumping Skid	Average Heat Load (kW)	Total Flow Rate (m^3/hr)	Temperature Range (^{o}C)
DTL20-1 (Prototype)	94	54	27±6

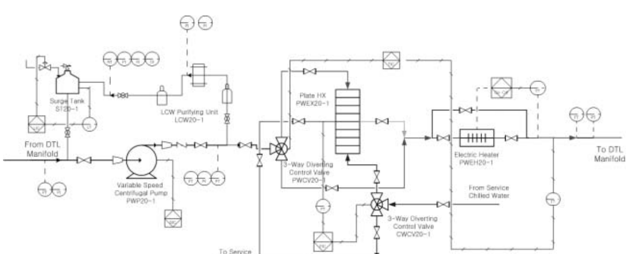

Figure 1: Flow diagram of water pumping skid.

The 3-way diverting electronically actuated control valve which is installed at the discharge side of pump directs a portion of the water to the heat exchanger, and the remainder of the flow through the by-pass line to regulate the mixed water temperatures supplied into DTL. The cold side of the heat exchanger is fed with chilled service water of 10 ^{o}C from the PEFP facility. To maintain steady flow on cold side of heat exchanger, the 3-way diverting electronically actuated control valve is also incorporated. PID controller adjusts the cold side control valve to adjust the chilled water flow rate into heat exchanger. This scheme is to compensate the nonlinear or disturbance characteristics of heat exchanger due to the variation of pressure drop between by-pass and heat exchanger.

The network model to calculate the process parameters of pressure drop and flow rate in DTL water cooling loop is shown in Fig. 2. The fluid network is comprised of flow paths that are joined at each node with major components of pump, heat exchanger, heater, control valve and DTL structures. To maintain flow rate and pressure balancing in closed loop, the pipe line size has been calculated based on flow velocity below 1.5 m/s for copper and 2.5 m/s for stainless steel to reduce the effect of erosion.

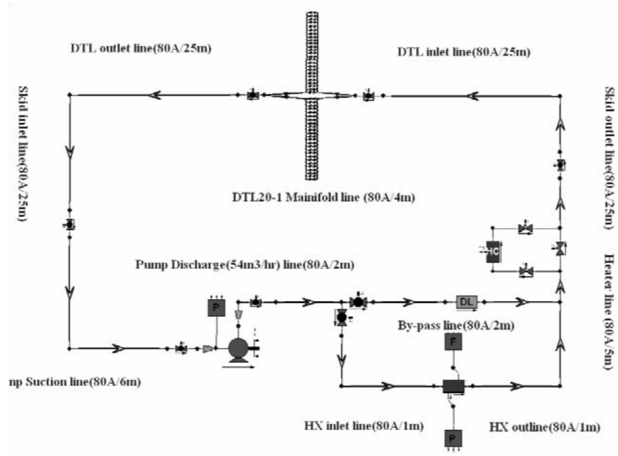

Figure 2: FLOWMASTER model of the pumping skid.

Total pressure loss is estimated as 4.05 kg/cm^2 and the main pipe is sized to 80A (3"). The pump driving power is about 10.5 kW for a maximum flow rate of 54 m^3/hr. The cooling performance of the pumping skid will be highly dependent on the design choice made for the liquid-liquid heat exchanger. The sizing of heat exchanger to meet the cooling capacity and pressure drop has been conducted with commercial program. The heat exchanger (gasket plate HE) has sized with a plate area of 0.125 m^2 and the number of plate from 61 to 67. With this type of heat exchanger, the temperature control range of ±6 ℃ will be possible in parallel with the cold side flow control (a maximum flow rate of 13.5 m^3/hr).

RESONANCE CONTROL MODELING

Using the Matlab/Simulink, the investigation of a wide range of operating issues during both transient and steady state operation has been conducted. The dynamic models of each subsection are grouped as RF power, DTL drift tube, cooling in drift tube, and heat exchanger with an assumption of the control valve model having perfect linear characteristics [5]. Figure 3 shows the transient response of average drift tube temperature, mixed water temperature and hot side inlet water temperature into heat exchanger during step change of control valve opening into heat exchanger loop. In this model, the initial temperature for cavity warming up by using heater is 33 ^{o}C during RF power turn-off. After RF powering of maximum duty of 24%, the tuned cavity temperature are decreased into 27 ^{o}C with cold side flow rate of 45%. At that, mixed water temperature is also decreased into 21 ^{o}C. From the simulation, when the control valve has opened with 15% flow in hot side heat exchanger loop, the tuned cavity temperature is estimated into 33 ^{o}C with the same cold side flow rate of 45%. Therefore, the size of heat exchanger selected will have a temperature control range of ±6 ^{o}C with a margin of cooling capacity of about 220%.

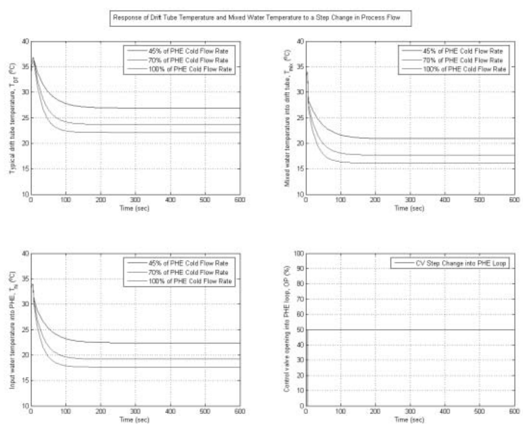

Figure 3: Temperature response of drift tube, mixed water and hot side inlet water for 24% RF duty under step change of control valve opening into heat exchanger loop.

To configure the response of resonance frequency shift, the step response of RF power from 0% duty (only EQM power loaded) to 8% duty has been induced in the same model conditions. At that, the frequency shift is adjusted into ±1 kHz with 90% opening of cold side flow rate and 50% opening of hot side flow rate in heat exchanger loop as shown in Fig. 4.

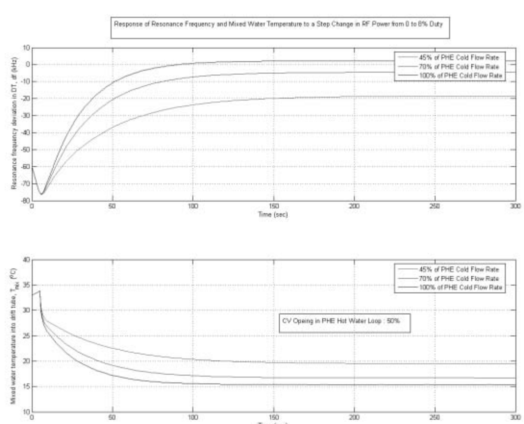

Figure 4: Frequency shift response at various cold side flow rate during the 50% valve opening in hot side loop.

TEMPERATURE CONTROL OF HEAT EXCHANGER LOOP

To understand the dynamic features and system modelling in the heat exchanger loop, the step test and PID tuning (relay tuning) have been performed with a conventional PID controller by using PEFP 20 MeV cooling system. Figure 5 shows the trends of auto-tuning process with set point variation, as of 30 and 35 ^{o}C, respectively. The PID tuning parameters, especially proportional gain, are appeared differently depending on the set point. Thus, to obtain the more stable temperature control, the gain scheduling with PID control scheme is estimated to be necessary to obtain more robust stability. Furthermore, the hot side outlet temperature droop is also appeared from the disturbance due to cold side inlet temperature variation.

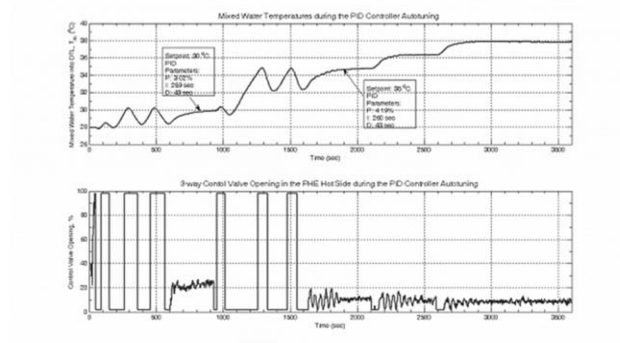

Figure 5: Temperature response of heat exchanger loop with PID relay tuning.

CONCLUSION

We have designed the PEFP DTL water cooling system for regulating the DTL drift tube resonant frequency. The PID algorithm for temperature and frequency control modes interfaced with LLRF system has been adopted for dynamic control of resonance. The PEFP team will fabricate the prototype of water pumping skid and test to verify the design performance of resonance conditions by using PEFP 20 MeV proton test facility in this year.

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