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Basic design of a 17-kW orifice type heater for the ESS cryogenic moderator system

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Abstract. At the European Spallation Source (ESS), a cryogenic moderator system (CMS) has been designed to circulate subcooled liquid hydrogen at 17 K and a flow rate of 0.25 kg/s per moderator. The nuclear heating corresponding to a 5-MW proton beam is estimated at 6.7 kW and is expected to increase to 17.2 kW for the four moderators in the future operation. The static and dynamic heat loads are dissipated by a 20 K helium refrigeration system, the Target Moderator Cryoplant (TMCP), with a cooling capacity of 30.3 kW at 15 K. When the proton beams are injected, a stepwise heat load applied to the hydrogen moderators results in a temperature rise of 1.76 K. To compensate for the transient heat load changes and ensure that the hydrogen supply temperature remains within $\pm$0.1 K of 17 K setpoint, a fast-response high-power heater was designed based on an orifice-type heater with a 5-kW capacity, originally developed by the author at J-PARC. Its geometry was optimized using computational fluid dynamics (CFD) to ensure that the heated surface temperature does not exceed 29 K, which is 2.6 K lower than its saturated temperature of 31.6 K at an operational pressure of 1.05 MPa.

1. Introduction

At the European Spallation Source (ESS), 2 GeV proton beams with a power of 5 MW are injected onto a rotating tungsten target wheel, operating at a repetition of 14 Hz and a pulse length of 2.86 ms, to generate high-energy spallation neutrons. These neutrons are subsequently slowed down to cold and thermal energies by a combination of hydrogen moderators and a light water premoderator, which are optimized to achieve high cold neutron brightness [1]. The resulting high brightness cold neutron beams will be utilized by scientific instruments for neutron scattering experiments. Currently, the ESS installs two hydrogen moderators positioned above the target wheel, with nuclear heating estimated at 6.7 kW for the 5-MW proton beam. In the future, this setup will be replaced with four-moderator configuration (two above and two below the target wheel), which is expected to increase the total nuclear heating to approximately 17.2 kW [2].

A cryogenic moderator system (CMS) has been designed to circulate subcooled liquid hydrogen at 17 K and 1.1 MPa, with a parahydrogen fraction exceeding 99.5% and a flow rate of 0.25 kg/s for each moderator, as shown in Fig.1 [3]. The heat load is effectively dissipated through a plate-fin exchanger by a large-scale 20 K helium refrigeration system, known as the Target Moderator Cryoplant (TMCP) with a cooling capacity of 30.3 kW at 15 K [4]. When the proton beams are injected, a stepwise heat load is applied to the hydrogen moderators, resulting in a 1.76 K increase in hydrogen temperature [5]. This temperature fluctuation propagates toward the heat exchanger at a flow velocity determined by the hydrogen circulation flow rate.

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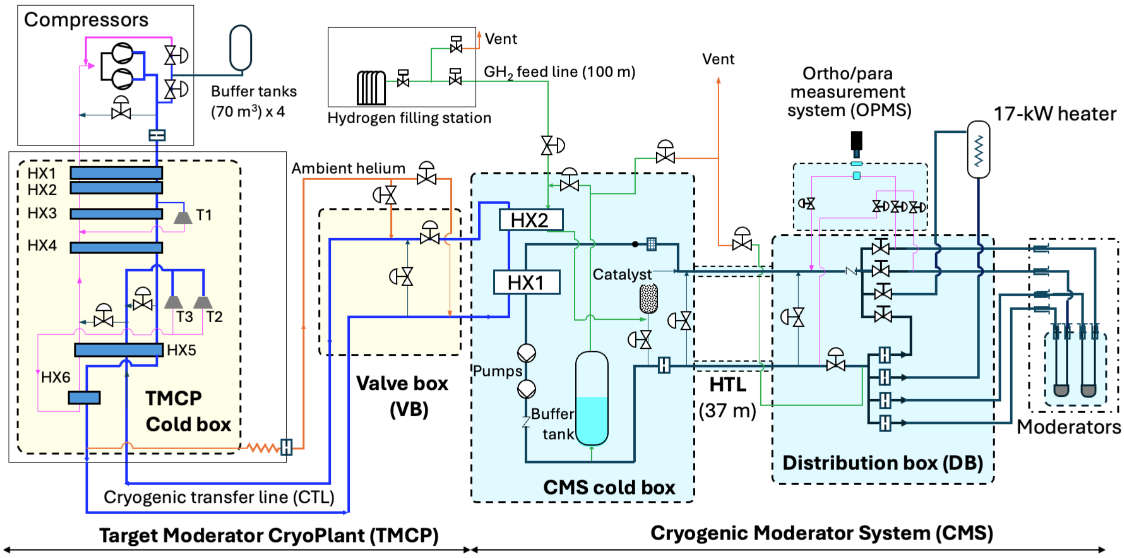

Figure 1. Overview of the cryogenic moderator system (CMS).

To compensate for the transient heat loads applied to the CMS, the ESS employs two approaches: a valve box integrated with the TMCP, and an electrical heater installed within the CMS loop. The valve box, located adjacent to the CMS cold box, regulates cooling power by adjusting the feed helium flow rate to the CMS without altering the TMCP operational conditions. As proton beam powers increase, a fast-response high-power heater becomes essential to ensure a stable hydrogen supply temperature of 17 K within ±0.1 K. The heater compensates for rapid nuclear heating of up to 17 kW without inducing thermal disturbances, thereby maintaining a constant heat load transferred from the CMS to the TMCP.

In this study, a 17-kW heater was designed based on the 5-kW orifice-type heater at the J-PARC developed by Tatsumoto et al. [6]. The heater geometry was optimized through CFD simulations using ANSYS FLUENT, ensuring that the heated surface temperature remains below 29 K, which is 2.6 K lower than its saturated temperature at an operational pressure of 1.05 MPa.

2. 17-kW heater design

2.1 J-PARC heater design

The J-PARC CMS circulates cryogenic hydrogen at 18 K under a supercritical pressure of 1.5 MPa with a flow rate of 162 g/s, ensuring that the temperature rise across each moderator remains below 3 K [7]. The nuclear heating is estimated to be 3.8 kW for a 1-MW proton beam operation. To enable a stable helium refrigerator operation, it was essential to keep a constant heat load on the refrigerator at the proton beam injection or trip events. Tatsumoto et al. [6] originally developed an orifice-type heater with rapid response capability and a maximum power of 5 kW to manage sudden variations in nuclear heating at the moderators. As shown in Fig. 2, the heater comprises ten U-shaped sheathed elements, each 12 mm in diameter and 1431 mm in

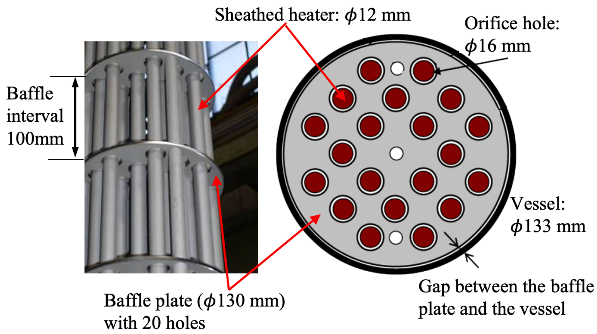

Figure 2. J-PARC orifice-type heater [6].

length, arranged in parallel. This configuration achieves an average heat flux of 4.9×10^3 W/m^3 at a total heater power of 5 kW. Baffle plates with 16 mm holes, through which the sheathed elements pass, are positioned longitudinally at 100 mm intervals to guide flow and promote uniform heating. The heater is installed downstream of the moderators, and is regulated by a PID controller to maintain a stable outlet temperature of 20.95 K. When the inlet temperature increases by 0.3 K due to beam injection, the heater power is rapidly reduced to compensate for the predicted nuclear heating. During 500-kW proton beam operation, it was verified that the heater successfully maintained the hydrogen supply temperature at 18 K within fluctuations of $\pm$0.1K, while enabling stable operation of the helium refrigerator [8].

2.2 ESS 17-kW heater design conditions

A high-power heater with a fast-response function and a maximum power of 17 kW is required to compensate for transient heat loads induced by the nuclear heating. The design is based on the J-PARC orifice type heater. The heater is integrated downstream of one of the future moderator distribution lines to maintain a hydrogen temperature of 19.5 K downstream of the merging point of the return distribution lines. The design conditions are as follows:

(1) The maximum power is 17.5 kW, providing a margin of 800 W.
(2) The maximum heated surface temperature must remain below 29 K, which is lower than its saturated temperature of 31.6 K at 1.05 MPa, to prevent flow instability caused by boiling.
(3) The maximum allowable pressure drop across the heater is limited to 30 kPa. The pressure drop across the entire moderator distribution line is estimated to be 78 kPa at 250 g/s [3].

As shown in Fig. 3, a sheathed heater element directly immersed in liquid hydrogen was selected to ensure a fast response. The heater wire, made of Nickel-Chrome alloy, is enclosed within a stainless-steel sheath. The gap between the wire and sheath is filled with oxide insulating powder to provide both electrical insulation and thermal conductivity. If boiling occurs on the heated surface, bubbles passing through the orifice section may increase pressure drop, potentially leading to flow instability.

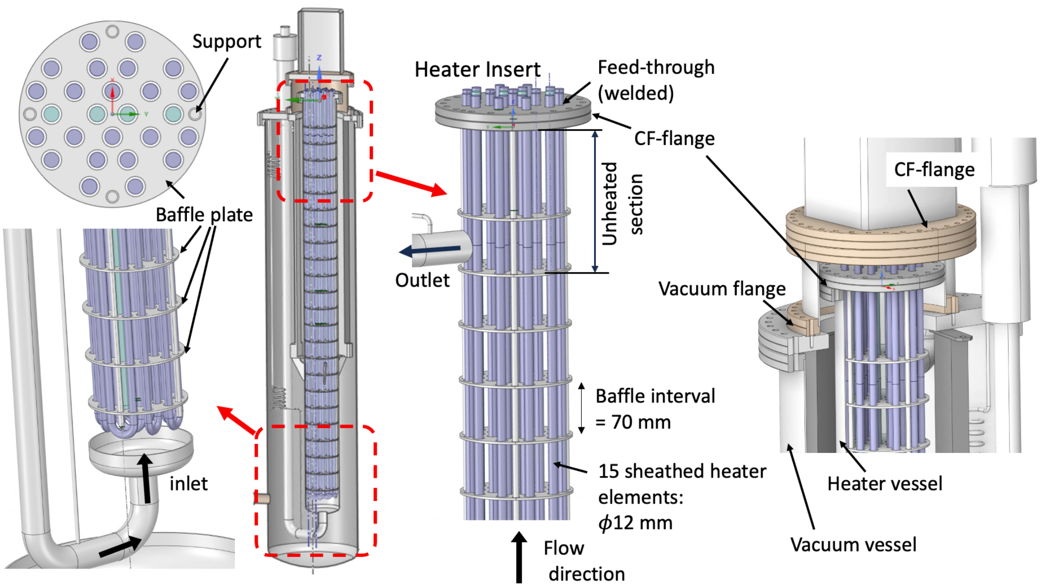

Figure 3. Overview of the designed 17-kW orifice-type heater for the ESS CMS.

Tatsumoto et al. [9-12] investigated forced convection and pool boiling heat transfer characteristics of subcooled liquid hydrogen over a temperature range of 20 to 31 K and pressures from 0.3 to 1.1 MPa. For natural convection and pool boiling heat transfer from a horizontal Pt-Co wire with a diameter of 1.2 mm [11], the onset of nucleate boiling at 1.1 MPa and 21 K was observed at a heat flux of 1.0×10^4 W/m^2. For forced convection heat transfer characteristics from Pt-Co wires with a length of 60 mm positioned along the central axis of a pipe with a diameter of 5.7 mm [12], the onset heat fluxes were 1.2×10^4, 3.1×10^4, and 4.0×10^4 W/m^2 for flow velocities of 0.65, 1.6 and 2.0 m/s, respectively. The experimental results showed that non-boiling heat transfer agreed well with the Dittus-Boelter correlation [13], and that the onset heat flux increases with both flow rate and subcooling. Based on these findings, the heat flux in the present heater design was set to remain below 1.0×10^4 W/m^2 to prevent nucleate boiling.

The diameter of the sheathed heater element was selected to match the 12 mm used in the J-PARC heater design. To achieve the required heat load of 17.2 kW, thirteen U-shaped sheathed heater elements were arranged in parallel, each with a heated leg length of 1.75 m. This results in a total of 26 heated legs across the cross section. The heater vessel has an inner diameter of 150 mm and a length of 1.8 mm. Each baffle plate is machined with 26 holes, each 16 mm in diameter, slightly larger than the heater elements, to create an orifice effect. The configuration is expected to improve heat transfer performance by inducing a stirring effect. Hydrogen flows upward from the bottom of the vessel. The average flow velocity through the orifice ranges from 1.5 to 2.1 m/s, corresponding to mass flow rates of 0.25 to 0.35 kg/s, respectively. Both ends of each sheathed element are welded onto the top flange. Baffle plates with a thickness of 3 mm and a diameter of 147 mm are longitudinally arranged at 70 mm, as determined from preliminary analysis results.

Since the outlet pipe is positioned near the top flange on the side of the vessel, gaseous hydrogen tends to accumulate in the region between the top flange and the outlet pipe. To prevent excess temperature rise on the heated surface, unheated sections with a length of 190 mm are incorporated at both ends of the heater elements. These sections extend from the top flange to the lower part of the outlet pipe, corresponding to the position of the second baffle plate.

The heater vessel is enclosed within an independent vacuum vessel with a diameter of 400 mm, located adjacent to the distribution box. The vacuum space is shared with the distribution box via the supply and return transfer lines, which are connected to one of the bypass lines designated for the planned future moderators. For maintenance and replacement purposes, the heater element insert is designed to be replaceable, with the CF-flange positioned above the vacuum vessel flange as shown in Fig. 3.

3. Analytical model

Figure 4 illustrates a simplified analytical model, where one of the heater elements and the surrounding liquid hydrogen are represented using a quarter-model approach. The diameter of the heater element is 12.0 mm as described in Section 2.2. In this model, the surrounding liquid hydrogen region is characterized by an equivalent diameter of 29.4 mm, corresponding to a cross-sectional area of 679.7 mm^2. This area represents the per-heater-element area, determined by dividing the vessel's cross-sectional area by the 26 heater elements. The baffles, with a thickness of 3.0 mm, are spaced at intervals of 73 mm.

The realizable κ-ε turbulent model with enhanced wall treatment was applied to the simulation. Momentum and turbulent equations were discretized using the first-order upwind differencing (UD) scheme, while the energy equation was discretized using the second-order UD.

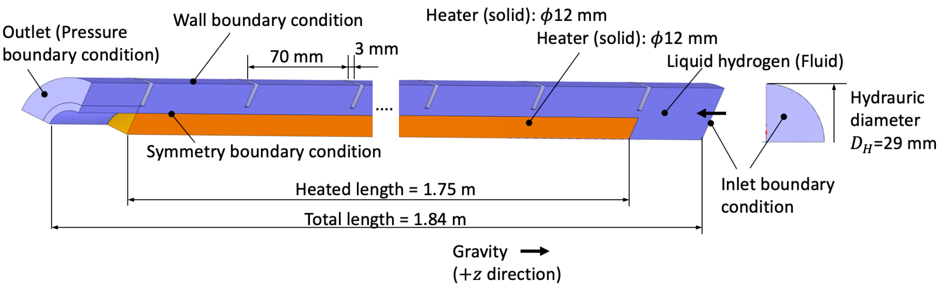

Figure 4. Analysis model.

Pressure field was calculated by SIMPLE algorithm (Semi-Implicit Method for Pressure-Linked equation). Buoyancy effects were considered in the analysis.

The inlet boundary conditions were set to a temperature of 18 K and a pressure of 1.0 MPa. Inlet flow velocities (u_{in}) of 0.20 m/s, 0.24 m/s, 0.28 m/s, and 0.32 m/s, corresponding to mass flow rates ($\dot{m}_h$) of 250 g/s, 300 g/s, 350 g/s, and 400 g/s, were applied to represent the liquid hydrogen passes through the heater vessel, were applied. Heat generation corresponding to the heat load was uniformly applied to the heater element. The heat generation rate ($\dot{Q}_V$) of 3.30×10^6 W/m^3 corresponds to a total heater power of 17 kW and a heat flux ($\dot{Q}_S$) of 9.91×10^3 W/m^2.

The properties of parahydrogen were modelled as polynomial functions of temperature, derived by fitting values obtained from the GASPAK [14]. Stainless steel properties were also treated as polynomial functions of temperature. Steady-state calculations were performed iteratively until the residual errors dropped below 10^{-4}.

4. Results and discussion

Figure 5 shows the simulation results of the pressure distribution along the heater element, from one end to the outlet boundary. The pressure distributions exhibit a staircase pattern as the hydrogen flow passes through each baffle plate. The pressure drop mainly occurs at each baffle and increases due to locally elevated flow rates, as shown in Fig. 6. Figure 7 shows the effect of the flow rate on the pressure drop. The pressure drop increased proportionally to the square of mass flow rate. The pressure drop is 3.6 kPa at a flow rate of 250 g/s, corresponding to the flow rate supplied to one moderator. Even when the flow rate increased to 400 g/s, the pressure drop only rose to 9.1 kPa, which remained well below the design criterion of 30 kPa. Tatsumoto et al. [16] reported that the pressure drop across equipment with a complicated shape in turbulence region can be expressed using a parameter dependent on the component geometry, F, as follows.

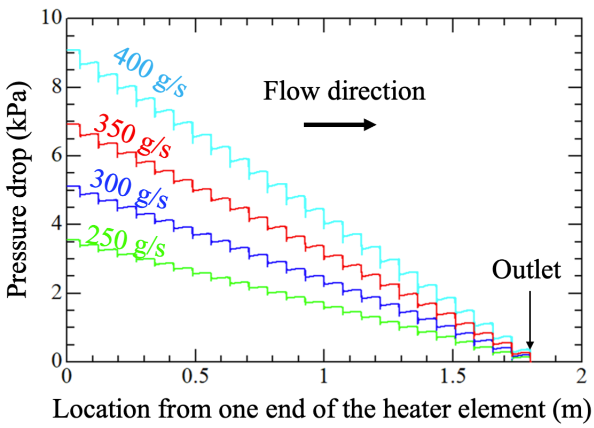

Figure 5. Pressure distribution along the heater.

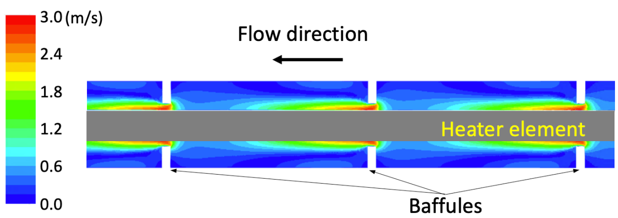

Figure 6. Flow pattern around the baffle plate at u_{in} = 0.28 m/s ($\dot{m}_h$=350 g/s).

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$$\Delta P = F\frac{\dot{m}^2}{\rho} \tag{1}$$

where $\dot{m}$ is the mass flow rate and ρ is the density.

The geometry factors, F, calculated from the pressure drops are shown in Fig. 8. The estimated geometry factors matched the identified value of 4.206×10^6 m^{-4}, independent of the flow rate. It was demonstrated that the pressure drops can be predicted using Eq. (1) within an error of less than 0.5%, as shown in Fig. 7.

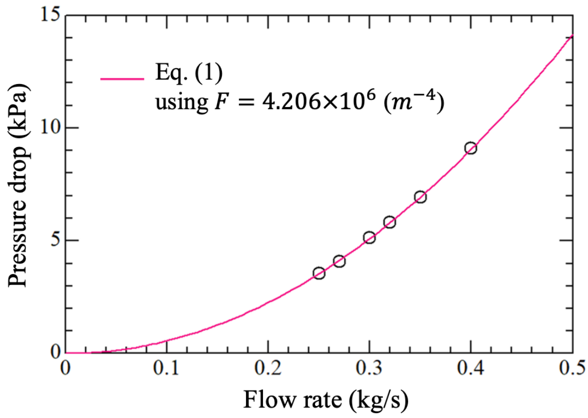

Figure 7. Pressure drop across the heater.

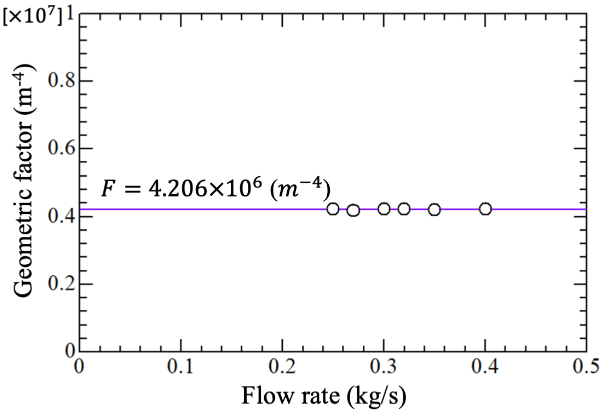

Figure 8. Estimated geometric factor for the heater.

Figure 9 shows the simulation results of temperature distribution at a heat load of 17.5 kW ($\dot{Q}_V$ =3.40× 10^6 W/m^3) and an inlet flow velocity of 0.25 m/s, corresponding to 320 g/s, as one example. The temperature of the heater element increases along its length. As the liquid hydrogen flows through the baffle plates, the flow velocity increased due to the constricting effect. The thermal boundary layer that develops above the heated surface is disturbed by the stirring effect of the baffles. The maximum heated surface temperature occurs approximately 13.5 mm upstream of each baffle plate. Figure 10 shows the distributions of the heated surface on the heater element (T_s) and the liquid hydrogen temperature at the wall boundary condition (T_b), with the lowest temperatures across the cross-section occurring at the same location relative to the inlet. The heated surface temperatures increase along the heater element. At the baffle plates, the heated surface temperatures are minimized due to the stirring effect the between the baffles. The temperature rise between the baffle (ΔT_s) is approximately 4 K for an inlet flow velocity of 0.196 m/s, equivalent to 250 g/s. Downstream of the heater element (at 1.2 m), the heated surface temperature exceeds the allowable design temperature (T_m) of 29.0 K, reaching 30 K at the final baffle plate. As the flow rate increases, the temperature

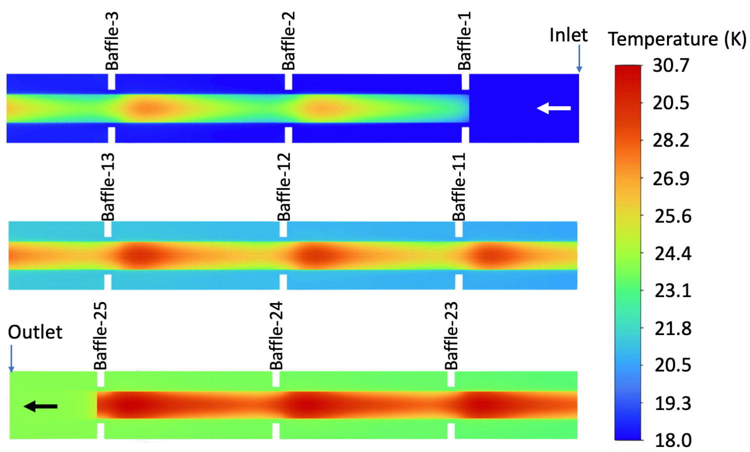

Figure 9. Temperature distributions along the heater element at a heat load of 17.5 kW.

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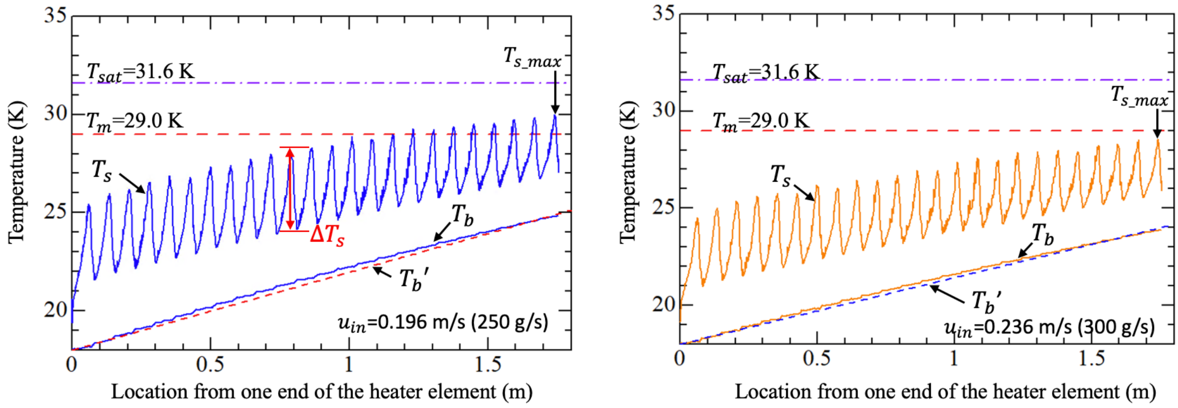

(a) u_{in}=0.196 m/s (250 g/s) (b) u_{in}=0.236 m/s (300 g/s)

Figure 10. Temperature distributions along the heater element at a heat load of 17.5 kW.

rise between the baffles (ΔT_s) decreases, and the maximum heated surface temperature also decreases. The average liquid hydrogen temperatures (T_b) on the wall boundary condition agree well with the temperatures predicted by a mass balance, using the flow rate and applied heat load. This suggests that the liquid hydrogen temperatures become uniform across the cross-section as it flows through the baffle plate, due to the stirring effect.

Figure 11 illustrates the allowable heater power at each flow rate ($\dot{m}_h$). The figure revealed that a flow rate higher than 270 g/s is required to meet the design heat load of 17.5 kW. A heat generation rate corresponding to a heat load of 19.7 kW represents the scenario where 12 heater elements are used, with one element kept as a spare. It is confirmed that the flow rate supplied to the heater must be adjusted to 330 g/s for this scenario. Furthermore, for the current two-moderator configuration, where the nuclear heating is 6.7 kW, the required flow rate through the heater is at least 100 g/s.

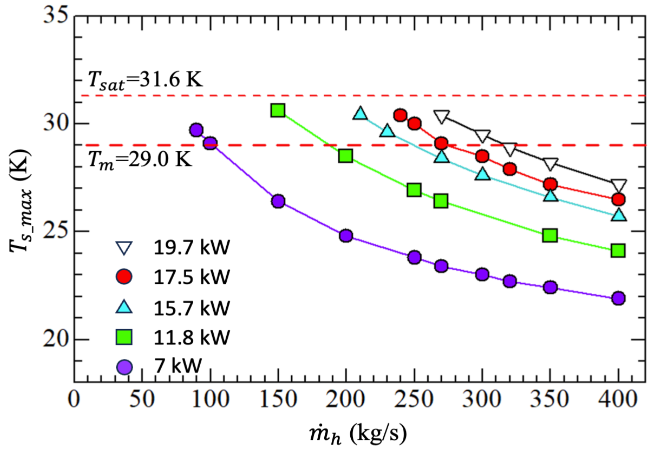

Figure 11. Relationship between $\dot{m}_h$ and T_{s_max} at each heat load.

Additionally, it was verified whether the following scaled-down model shown in Fig. 12, which simplifies the full twenty-five baffle model to a four-baffle configuration, could be used to determine and optimize the heater design parameters during the design phase in order to reduce the computational load. The inlet temperature can be specified based on the temperature predicted by a thermal balance at the corresponding location, as the liquid hydrogen temperature becomes uniform after passing through the baffle plate, as previously described. Figure 13 compares the results from the scaled-down model with those from the full model. The temperature distributions of the heated surface downstream of the second baffles agree well with those of the full-model, except in the region between the first and second baffles. This demonstrated that the scaled-down model is suitable for estimating the temperature distribution between the baffles and T_{s_max} when evaluating heater design parameters.

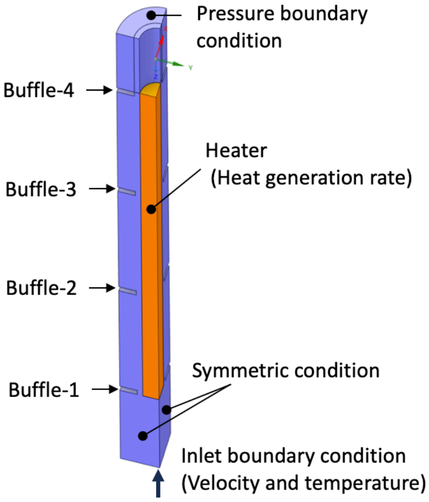

Figure 12. Scaling-down model.

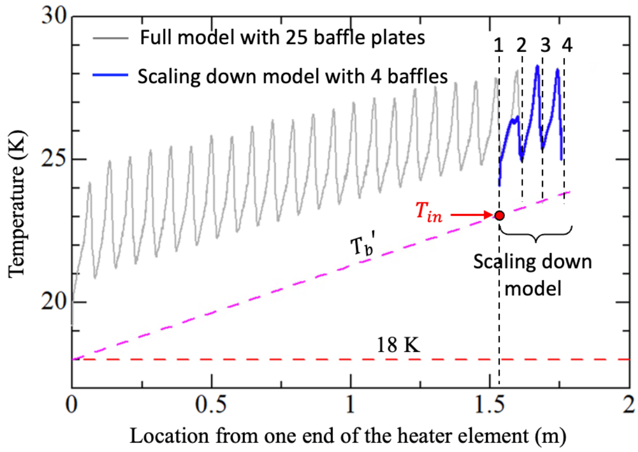

Figure 13. Verification of the scaling down model.

5. Conclusions

A 17-kW heater with a fast-response function was designed to compensate for the nuclear heating generated at the moderators, enabling a stable operation of the TMCP and CMS. The design was based on a 5-kW orifice-type heater originally developed at J-PARC. For the current two-moderator and the future four-moderator configurations, which correspond the required heater powers of 7 kW and 17.5 kW, flow rates through the heater of 100 g/s and 270 g/s were necessary to maintain the heated surface temperature below 29 K. The CFD simulation results confirmed that the optimized geometric parameters of the heater satisfied the design requirements.

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