Parametric Analysis of the In-bed gas flowing calorimetry of metal hydride bed employed in CFETR SDS

Peng Fan¹,², a, Wanfa Fu¹, *, Ming Wen², b, Zhi Zhang², c, Tao Tang², d and Quan Tang¹, e

¹School of Nuclear and Technology, University of South China, Hengyang 421001, China;
²Institute of Materials, China Academy of Engineering Physics, Jiangyou 621908, China;

*Corresponding author e-mail: fuwanfa@163.com, *251641821@qq.com,
bwenming2015@caep.cn, czhangzhi@caep.cn, dtangtao_my@163.com,
etangquan528@sina.com

Abstract. Gas flow calorimetry is considered to be one of the most promising tritium measurements method in fusion fuel cycles, yet the parametric study of the structure design is still insufficient. In this study, three-dimensional models, combining with commercial computational fluid software, has been used to evaluate the calorimetric performance of tritium storage beds. The effects of structural geometry and cooling method on the heat transfer behavior have been systematically studied. The results show that the proposed model can effectively characterizes the evolution of the temperature difference of the cooling gas with time during the calorimetric process. Typically, increasing number of the U-shaped cooling tubes, thickness of the metal hydride layer and flow rate of the cooling liquid are beneficial for reducing the thermal equilibrium time. When the number of calorimeter bed cooling tubes is 12, the thickness of the metal hydride layer is 23, and the cooling gas is 20 SLMP of CO₂, the thermal equilibrium time is only 4.5h. Furthermore, through optimizing the structural parameters, which can have an important influence on calorimetric performance, highly efficient and accurate gas flow calorimeter can be developed in the future.

1. Introduction

With the frame of future nuclear fusion reactors CFETR, tritium in kilograms will be handled in the tritium plant. For safety operation of tritium, the reactor system must implement an appropriate tritium tracking plan to prevent accidental tritium release events that cause the radiation dose to the public to exceed predetermined limits. Tritium tracking is to measure the tritium inventory and calculate the source term to determine the mobilizable tritium inventory in the vacuum vessel.[1, 2] To reduce the tritium tracking uncertainty. It is usually necessary to periodically transfer the tritium gas in the fuel cycle (FC) system to the storage and delivery system (SDS) and determine the amount of tritium that can be moved by appropriate measurements. The measurement method of SDS system is usually called in-bed calorimetry. In-bed calorimetry is considered to be one of the most promising measurement technologies due to its measurement safety and reliability. The in-bed calorimetry measurement mainly
uses the thermal effect of the measured sample, and its measurement performance is governed by several key factors, such as material characteristics, structural arrangement, and cooling system. Therefore, a comprehensive understanding of the coupling of heat transfer behavior with multiphysics is essential for the calorimetric performance in a bed. For the research of calorimetry behavior in the bed, a lot of work has focused on the design of the bed structure and the selection of the cooling medium, which will affect the calorimetric performance.

Earlier J.E.Klin et al. [3] proposed the concept of a gas flow calorimeter for measuring tritium in a bed and analyzed the influence of cooling gas on measurement linearity under different flow rates. Then, hayashi et al. [4-6] developed a calorimeter in the bed, which was claimed to meet the ITER design requirements, using a Zirconium-Cobalt (Zr-Co) alloy for the storage material. Eun-Seok Lee et al. [7] through numerical simulations believe that choosing an appropriate number of cooling pipes can effectively shorten the measurement time and reduce heat radiation loss. Hyun-Goo Kang et al. [8, 9] simulated the influence of different cooling gas flows and container temperature on calorimetric performance, and found that the faster the flow rate, the closer the main container temperature is to the equilibrium temperature, and the shorter the instrument reaches the thermal equilibrium time.

In those studies, although it can be clearly seen in the above literature that the performance of the gas flow calorimeter is affected by many aspects. The effects of structural parameters, cooling methods and thermophysical properties of materials on measurement time and accuracy have not been systematically studied. Therefore, the work of this paper aims to analyze the thermal performance of the calorimeter bed by 3D numerical simulation, taking into account the layout of U-shaped cooling tubes, the thickness of the metal hydride layer, the type of cooling gas, and the influence of the cooling gas flow. The obtained heat transfer information provides the possibility to develop a gas flow calorimeter for tritium plant applications.

2. Modeling of the SDS bed

2.1. Model

The calorimeter bed structure is shown in Fig. 1. The tank wall is composed of 3mm thick SUS 316L stainless steel. The shape of the entire container is a cylindrical ring structure with the axial length of 170mm. A cooling gas pipe with a diameter of 7mm is embedded in a metal hydride layer in a ring to form a plurality of circulating pipes. The metal hydride layer is composed of small particles of ZrCo, because ZrCo has been shown to have great development prospects in future tritium storage.

![Figure 1. Schematic geometry of the calorimeter bed used in the work](image-url)

2.2. Boundary conditions

Fig.2 shows the cross-section of the primary vessel of a gas flowing calorimeter bed, this model simulates the thermal performance of a tritium inventory at 50g at room temperature. some preliminary assumptions in this study are for analytical purposes.
- The circulating gas in the cooling gas pipeline is the ideal gas.
- Metal hydride, ZrCoT$_x$ is uniformly distributed in the metal hydride layer and the tritium inventory is 50g.
- All outer surfaces of the primary vessel wall and the cooling gas duct wall are adiabatic.
- The volume change of metal hydride was ignored at different tritium inventories.
- The initial temperature of the primary vessel was 308.15K.
- The inlet of the cooling gas circuit is given a fixed temperature and mass flow rate boundary.
- The outlet of the cooling gas circuit is given a relative pressure boundary.
- Defining the metal hydride layer as a subdomain gives a 16W volume source to simulate the decay energy of a 50 g tritium inventory.

![Figure 2. The cross section of primary vessel for gas flowing calorimetry](image)

2.3. Operating condition of the gas flowing calorimetry

Gas flowing calorimetry is performed by measuring the temperature difference between the inlet and outlet of the cooling gas circuit and the mass flow rate in the bed. The error sources include errors of mass flow rate, temperature difference between inlet and outlet, and tritium decay heat. It is assumed in this simulation that the cooling gas circuit completely removes the decay heat.[7]

The heat discharged from the cooling gas circuit can be calculated by the following formula:

$$Q = \dot{m}C_P \Delta T$$

(1)

Where $Q$ is the heat absorbed by the cooling gas circuit; $\dot{m}$ is the mass flow of the cooling gas; $C_P$ is the specific heat of the cooling gas, which is assumed to be constant here; $\Delta T$ is the temperature difference between the cooling gas at the inlet and outlet of the cooling circuit in the bed;

Tritium inventory calculation formula is as follows:

$$I = \frac{Q}{Q_T}$$

(2)

Where $I$ is the inventory of tritium (g); $Q_T$ is the decay heat per gram of tritium, 0.324W/g.

Assuming that the temperature of the cooling gas at the inlet of the cooling circuit in the bed is 35 °C, the error calculation formula is as follows:

$$\frac{\delta I}{I} = \sqrt{\left(\frac{\delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\delta (\Delta T)}{\Delta T}\right)^2 + \left(\frac{\delta Q_T}{Q_T}\right)^2}$$

(3)
\( \frac{\delta I}{I} \) is the error ratio for measuring tritium inventory; \( \frac{\delta m}{m} \) is the error ratio for measuring mass flow ratio (0.007); \( \frac{\delta Q_T}{Q_T} \) is the error ratio of tritium’s own total decay heat (0.9/324); \( \frac{\delta (\Delta T)}{\Delta T} \) is the error ratio for measuring temperature difference.

In order to achieve the measurement accuracy of 1% in the ITER design, it can be known from the formula (3) that the temperature error ratio is less than 0.007 \( \left( \frac{\delta (\Delta T)}{\Delta T} \leq 0.007 \right) \).

3. Result and discussion

3.1. Effect of the cooling tube pattern

In the model, a cooling gas pipe is embedded in a metal hydride layer in a ring to form a plurality of circulating pipes. The cooling gas takes out the decay heat generated by the tritium in the metal hydride through the circulation pipe. The number and arrangement of U-tubes are used to study the influence of the characteristics of the cooling tube structure on the heat transfer performance of the calorimeter.

The evolution of the cooling gas temperature difference (\( \Delta T \)) over time for different pipe structures is shown in Fig.3. In all pipe structure models, the temperature difference increases logarithmically with time, and a definite thermal equilibrium time constant can be observed in each model. When the number of U-tubes is 12, it shows a small thermal equilibrium time constant. Specifically, when the number of U-shaped pipes is 6, 10 and 12, respectively, the time required for the deviation ratio \( \frac{\delta (\Delta T)}{\Delta T} \) of several models to be less than 0.007 is 18.5, 16.5 and 14.5h. This shows that increasing the number of pipes is conducive to increasing the convective heat transfer area, thereby reducing the heat equilibrium time.

![Figure 3](image)

**Figure 3.** Dependence of thermal equilibrium time on the number of U-shapes. Evolution of temperature difference with time (a), evolution of temperature difference deviation rate with time (b).

3.2. Effect of the metal hydride layer thickness

The dependence of the calorimetric thermal equilibrium time on the thickness of the metal hydride layer is depicted in Figure 3. In order to keep the volume constant during the simulation, the model changes the axial length of the tank while changing the thickness of the metal hydride layer. It is found from this figure that a decrease in the thickness of the metal hydride layer increases the thermal equilibrium time. At the same time, it is found from Fig.4 (b) that the time to reach the target accuracy by reducing the thickness also increases, indicating that the level of heat transfer is reduced. It can be attributed to the fact that a reduction in the thickness of the metal hydride layer increases the convective heat transfer area, resulting in an increase in the convective heat transfer coefficient. On the other hand, the axial length of the main container increases the total heat capacity, which slows down the speed of thermal
equilibrium. From the overall effect, the inhibition effect is stronger than the promotion effect, which makes the overall heat balance time increase.

### 3.3. Effect of cooling medium

Several economical and commonly used cooling gas media are selected to perform a comparative on its dependence of calorimetric performance. For the analytical purpose, the gas flowing rates are chosen as 10 SLPM. It was found by Reynolds number that when the fluid flow rate was 10 SLMP, only carbon dioxide was in a turbulent state and the other cooling media were in a laminar state. Fig. 5 depicts the effect of different cooling mediators on the calorimetric performance when there are 10 U-shaped annular pipes. It can be observed that when the cooling medium is helium and nitrogen, the target accuracy cannot be achieved within 24 hours. However, using carbon dioxide as a cooling medium can achieve the target accuracy within 9 hours and has better calorimetric performance.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** Dependence of thermal equilibrium time on metal hydride layer. Evolution of temperature difference with time (a), evolution of temperature difference deviation rate with time (b).

**Figure 5.** Dependence of heat equilibrium time on cooling medium. Evolution of temperature difference with time (a), evolution of temperature difference deviation rate with time (b).

In actual experiments, due to the temperature difference between the bed and the outside, part of the energy inside the bed will be lost though thermal radiation. Therefore, it is necessary to control the steady-state temperature different between the inlet and outlet of the cooling gas. Figure 6 illustrates the effect of several cooling media on the calorimetric performance at the same steady-state temperature difference, it is observed in Fig.6 that at the same temperature difference, the temperature difference of
carbon dioxide changes faster, while the temperature difference between nitrogen and helium changes almost the same. It can therefore be concluded that carbon dioxide is suitable as an ideal coolant.

Figure 6. Dependence of thermal equilibrium time and cooling medium at the same temperature difference. Evolution of temperature difference with time (a), evolution of temperature difference deviation rate with time (b).

3.4. Effect of the flow rate

The role of the cooling gas medium is to dissipate the heat generated by tritium decay. Therefore, it can be guessed that the motion state of the fluid in the cooling tube affects the heat transfer performance. In this work, in order to study the dependence of the heat diffusion of the primary vessel on the flow velocity of the cooling gas, the carbon dioxide flow rate in the cooling pipe was set as 5, 10, 15, and 20 standard liter per minutes (SLMP). Table 1 provides the convective heat transfer coefficient and Reynolds number of several flow rates. It can be seen from the Reynolds number that when the flow rate is 5 SLPM, the fluid flow exhibits layer flow behavior. When the flow rate is 10 SLPM, 15 SLPM and 20 SLPM, the fluid flow shows turbulent behavior.

Figure 6 shows the evolution of temperature over time at several flow rates. In the cases of flow rates at 5 SLMP, it takes more than 24 hours for ΔT to reach steady state. For the cases of flow rates at 10 SLPM, 15 SLMP and 20 SLPM, it takes less than 10 hours. For detailed analysis, the deviation ratio \( \frac{\delta(\Delta T)}{\Delta T} \) is shown in Fig.7. When the cooling gas flowing rate is changed from 5 SLPM to 10 SLPM, it has a significant effect on the deviation rate \( \frac{\delta(\Delta T)}{\Delta T} \). In other words, as the flow rate becomes larger, the deviation ratio \( \frac{\delta(\Delta T)}{\Delta T} \) decreases more significantly. This can be explained from Reynolds number. When the flow rate changes from 5 SLPM to 10 SLPM, the fluid flow mode changes from laminar to turbulent, which promotes convective heat transfer. If the flow rate is accelerated from 10 SLMP to 15 SLPM and 20 SLPM, the heat transfer capacity is improved. But as the flow rate increases, the steady-state temperature \( \Delta T_{ss} \) will be reduced. In practice, the low steady-state temperature will cause greater measurement errors due to the influence of ambient temperature. Therefore, the optimal flow rate should be determined by the actual error.

Table 1. Reynolds number and convective heat transfer coefficient at different flows.

| Fluids | 5 SLMP | 10 SLMP | 15 SLMP | 20 SLMP |
|--------|--------|---------|---------|---------|
| Re     | 1769.9 | 3521.4  | 5281.9  | 7042.7  |
| \( h_{m}, \text{W/(K·m}^2) \) | 7.9    | 27.2    | 37.6    | 47.3    |
Figure 7. Dependence of heat equilibrium time on cooling gas flow. Evolution of temperature difference with time (a), evolution of temperature difference deviation rate with time (b).

4. Conclusion
A ring-shaped calorimeter bed was proposed in this work. Thermodynamic analysis of the bed was performed using commercial computational fluid dynamics software. The influence of the structure geometry and cooling mode of the calorimeter on temperature evolution was studied. The results obtained will be used to develop calorimeter beds for tritium plant applications.

Some conclusions are summarized as follows:
1. The effect of the cooling system on the thermal equilibrium time is critical. In the analysis of three commonly used cooling gases, CO$_2$ was found to be an attractive coolant.
2. Increasing the flow rate of the cooling gas can effectively reduce the caloric equilibrium time in the bed, but from the influence of indoor temperature fluctuations and instrument errors, the lower temperature difference of the cooling gas will bring greater measurement uncertainty. Therefore, the selection of the optimal flow rate of the cooling gas needs to be determined from actual experimental conditions.
3. Decreasing the thickness of the hydrogenation layer will lead to an increase in the thermal equilibrium time, which is caused by the increase in the overall heat capacity of the calorimeter. This factor needs to be considered when designing the calorimeter bed.
4. More cooling tubes can effectively increase the heat transfer area between solids and fluids, thereby speeding up heat transfer and reducing thermal equilibrium time.

Finally, it is worth noting that the information provided here does increase understanding of the factors affecting calorimetric performance. However, the heat transfer behavior of tritium measured by gas flowing calorimetry involves convective heat transfer, radiant heat transfer, and heat transfer. Therefore, considering heat transfer behavior only in the ideal case does not seem to be sufficient to fully evaluate the performance of the calorimeter.

At present, we are setting up a gas flowing calorimeter experimental platform. A comprehensive analysis of the heat transfer behavior of the calorimeter is the subject of our further research.

References
[1] U. Engelmann, G. Vassallo, A. Perujo, D. Holland, Fusion Technology, 28 (1995).
[2] D. Murdoch, I.-R. Cristescu, R. Lässer, Fusion Engineering and Design, 75-79 (2005) 667-671.
[3] J.E. Klein, M.K. Mailory, A. Nobile, Fusion Technology, 21 (1992) 401-405.
[4] T. Hayashi, T. Suzuki, M. Yamada, M. Nishi, Fusion Technology, 34 (1998) 510-514.
[5] T. Hayashi, T. Suzuki, M. Yamada, M. Nishi, Fusion Science and Technology, 48 (2005) 317-323.
[6] T. Hayashi, M. Yamada, T. Suzuki, Y. Matsuda, K. Okuno, Fusion Technology, 28 (1995) 1015-
1019.

[7] E.-S. Lee, S. Cho, M.-Y. Ahn, D.H. Kim, M.-H. Chang, H. Chung, M. Shim, K.-M. Song, S.H. Sohn, D. Kim, H. Yoshida, Fusion Engineering and Design, 83 (2008) 1424-1428.

[8] H.-g. Kang, S. Cho, M.H. Chang, s.-h. Yun, K.-S.J. Jung, H.S. Chung, M.-B. Shim, D.S. Koo, K.M. Song, Parametric analysis of the helium flow for the in-bed calorimetry of metal hydride bed, 2009.

[9] H.-G. Kang, E.-S. Lee, S. Cho, M.H. Chang, S.-H. Yun, M.-Y. Ahn, K.J. Jung, H. Chung, M. Shim, K.-M. Song, H. Yoshida, Fusion Engineering and Design, 84 (2009) 989-992.