Characterization of a real-time neutron imaging test station at China Advanced Research Reactor

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Abstract

A real-time neutron imaging test station was recently installed at the China Advanced Research Reactor. The objective of this work was to determine its operational characteristics, including neutron beam profile, the spatial resolution and time resolution. The performance of the equipment was demonstrated by a real time neutron imaging test of the water dynamics in a fuel cell.

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1. Introduction

Analysis techniques based on dynamic neutron imaging are a powerful tool to investigate fast processes in various fields, such as water flow management of fuel cell (D. Kramer et al., 2005; T.A. Trabold et al., 2006), two-phase flow (N. Takenaka et al., 1999; J.E. Cha et al., 2005), etc. China Advanced Research Reactor (CARR) is a 60-MW tank-in-pool type reactor (D.F. Chen et al., 2006), with an expected maximal undisturbed thermal neutron flux of $8 \times 10^{14}$ cm$^{-2}$s$^{-1}$. As a multi-purpose research reactor, CARR is devoted to neutron scattering, neutron imaging, radioisotope production, neutron transmutation doping of silicon, neutron activation analysis, and so on.

Recently, a real-time neutron imaging test station was installed at the end of the CNGA neutron guide for studying the methodology of high-speed imaging. The objective of this work is to fully characterize its key specification involving neutron beam profile, the time resolution and spatial resolution. Moreover, its performance had been tested through the experiment of observing water dynamics in a fuel cell.

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2. Experimental set-up

The real-time neutron imaging test station was installed at the end of the curve cold neutron guide CNGA (the cold source will be available in 2016), which is located at the neutron guide hall of CARR. It consists of 3.75m in-pile guide, 17m curve guide and 8m straight guide. This guide has $30\times150$ mm$^2$ cross section, 1.88Å characteristic wavelength, and $m=2$ supper-mirror coating. The imaging test station is located at 2.6m away from the end of CNGA. Between the guide and imaging equipment a shutter is installed, made of 15cm thick boron polyethylene and 5cm thick lead. Figure 1 shows a simplified view of the CNGA guide with its horizontal accesses.

![Fig. 1 Layout of CNGA guide with its horizontal accesses.](image)

Figure 2 shows the present status of the installed setup. Its detection system (Linfeng He et al., 2013) consists of a scintillator converter screen, a mirror and a commercial sCMOS camera (Colin Coates et al., 2009). The scintillator screen is 0.5-mm thick and 20cm*20cm field of view based on $^6\text{LiF/ZnS}$ co-doped with Ag. The camera is a PCO-Edge type (PCO optics, USA), equipped with a sCMOS sensor, with 2,560×2,160 pixels (6.5×6.5 μm$^2$ size) and peak efficiency of 45% at 450nm. A 50 mm/f=0.9 lens is used and an adapter ensures a lens-to-camera distance. In order to minimize gamma exposure of the camera it is shielded in a 2cm thick lead box.

3. Results

3.1 Beam profile:

The neutron flux was measured to be $4.25\times10^7$ cm$^{-2}$s$^{-1}$ at the beam center at 10MW reactor power using the gold foil activation method. Neutron beam distribution had been investigated by using MC Simulation and neutron imaging (see figure 3). The beam distribution of the simulated results agrees very well with the measured, except the defect at the bottom which is caused by the limited size of scintillator. The effective beam size (down to 50% peak flux) is around 3.2cm*16cm measured from the flat field image.
Fig. 3 The neutron beam distribution at the scintillator screen. (Left: Calculated by MC simulation with Vitess, Right: measured by neutron radiography) unit: cm

Fig. 4 Neutron image of the flat field using pinhole

Fig. 5 Distribution of beam intensity horizontal and vertical direction respectively
A 2mm pinhole aperture made by 1mm think Cd sheet was located at 0.8m away from the end of the CNGA guide. According to the pinhole image size (figure 5) and Eq (1), the $L/D$ value could be estimated to 90 and 145 at vertical and horizontal respectively.

$$\frac{L}{D} = \frac{s - r}{l}$$  \hspace{1cm} (1)

$s$ is FWHM of image size(figure 5), $r$ is pinhole dimension, and $l$ is distance between pinhole and image.

3.2 Spatial resolution:

The spatial resolution of the radiographic system was evaluated by analyzing the image of a high contrast sharp edge, based on the Edge Spread Function (ESF) and the Modular Transfer Function (MTF) (Yu Wang et al., 2012). A gadolinium slab with the thickness of 200μm was irradiated in close contact to the scintillator screen. Figure 6 shows the edge spread function fitted to the gray-level intensity distribution (M.A. Stanojev Pereira et al., 2008; A.A. Harms et al., 1972):

$$ESF = p1 + p2 \times a \tan (p2 \times (x - p4))$$  \hspace{1cm} (2)

Where $p1$, $p2$, $p3$, and $p4$ are free parameters and $x$ is the scanning coordinate.

The corresponding MTF (see figure 7) was obtained from the ESF derivated by Fourier transform. The spatial frequency corresponding to the MTF value of 0.1 was considered as the spatial resolution of the imaging system in lp/mm. The evaluated resolution was 0.34 mm (1.46 lp/mm), calculated from an average of ten distinct values determined in ten distinct regions of the edge object, among which five were performed in each in horizontal and vertical direction, respectively. It was the ideal resolution value, as the distance between the object and the scintillator screen was approximated to zero.

According to our previous work (Linfeng He, et al., 2014), the overall spatial resolution of the system is affected by the distance $d$ between sample and scintillator, collimation ratio $L/D$, scintillator spread spot eigenvalue $\delta$, and effective pixel size at scintillator $\Delta s / M_{CCD}$, as described in Eq (3).
When $d=0$, $\Delta s / M_{\text{CCD}} = 0.138 \text{ mm}$, $u = 1.46 \text{ lp/mm}$ and $MTF(u) = 0.1$, the scintillator spread spot eigenvalue was calculated to be $\delta = 0.28 \text{ mm}$. Considering that normal object–scintillator screen distance is less than 4 cm (the collimation $L/D$ ratio = 90), according to Eq(3), the system spatial resolution should be between 0.34 mm and 0.52 mm.

### 3.3 Time resolution

Time resolution depends on the camera scan speed, the neutron flux and the signal-to-noise level. Table 1 shows the maximum camera speed at various exposure areas. For low resolution and small effective sensor sizes the camera reaches close to 1000 fps scan speed.

<table>
<thead>
<tr>
<th>Sensor area</th>
<th>Max frame rate of sCMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2560×2160</td>
<td>100 fps</td>
</tr>
<tr>
<td>1280×1024</td>
<td>212 fps</td>
</tr>
<tr>
<td>640×480</td>
<td>450 fps</td>
</tr>
<tr>
<td>320×240</td>
<td>893 fps</td>
</tr>
</tbody>
</table>

The camera could achieve 16000 grey levels in the beam center at 1 sec exposure time at a neutron flux of $4.25 \times 10^7 / \text{cm}^2/\text{s}$ at 10 MW. It was estimated that around 90 grey levels will be reached at 1000 fps scan speed when the reactor is operated at full power (60 MW, without the cold source). The signal to noise ratio is

$$
\frac{s}{n} = \frac{N}{\sqrt{\sigma_s^2 + \sigma_r^2 + \sigma_s^2}} = \frac{N}{\sqrt{N + \sigma_r^2 + \sigma_s^2}}
$$

(4)

$N$ is grey level, $\sigma_s$ is statistic noise which is $\sqrt{N}$, $\sigma_r$ is readout noise, and $\sigma_s$ is dark current which is neglected here.

Considering that its read-out noise is $2.2 \text{ e-}$, corresponding to grey level 4.9, the signal to noise ratio is 8.4.
value would be improved significantly if the cold source is available or binning the pixels.

A real-time imaging experiment of a rotating computer cooling fan was carried out at a reactor power of 10MW to test the system performance in an extreme condition. As shown in figure 8, the left picture was a static neutron image of the fan when the exposure time was 1 sec and the right one is a single frame of a high speed movie of the neutron irradiated fan with a frame rate of 1000fps (per frame the exposure time was 0.9 msec). The outline of the fan can be recognized in the image though the maximum grey level is only 14.

![Image of cooling fan](image)

**Fig. 8** The neutron images of a cooling fan of a GPU, measured at 10MW. Left: static image (exposure time is 1 sec), Right: one frame of the dynamic images at 1000fps.

### 3.4 Real time neutron imaging test of fuel cell

Fuel cell represents a promising alternative to internal combustion engines in cars since it can be integrated in an energy conversion chain using renewable sources and reducing polluting emissions. However, water management is still one of the key issues limiting the widespread use of fuel cell. Operating parameters, material properties and flow field geometry have a deterministic role on the water storage and distribution within the flow channels and porous media in a fuel cell. Neutron imaging has played a significant role in describing the correlation between current density and measured total water content and its distribution in operating fuel cells. Real time neutron imaging of the water flow (or dynamics) in fuel cell was performed and demonstrated the potential of the presented setup for such investigation.

For the first measurement set, the fuel cell was dried at room temperature for several days and a set of 10 individual images obtained in 20 sec (the maximum exposure time of this camera is 2 sec) have been captured at 10MW. For the second set of measurements the flow channels of the fuel cell were fully immersed in water at first, then heated up to fuel cell working temperature of 70°C, and air was blown into the channels at 50 ml/s speed. During this procedure, 900 individual images were captured at the same conditions as in the first set. Figure 9 showed the photograph and the neutron radiograph of the fuel cell which had been calibrated by the flat field and the dark field images.

![Image of fuel cell](image)

**Fig. 9:** Real-time neutron imaging test for the water process of fuel cell.

Left: Photography of fuel cell; Right: One frame of neutron images of fuel cell after normalization.
The water distribution can hardly be distinguished in the normalized neutron image. In order to show only the water distribution the image of the dry fuel cell was subtracted from the wet cell, using Eq (5).

\[ I = -\ln \frac{I_1}{I_2} = -\ln \frac{I_0 \exp(-\Sigma_w x_w - \Sigma_n x_n)}{I_0 \exp(-\Sigma_n x_n)} = \Sigma_w x_w \] (5)

\( I \) was the neutron path length of water in the neutron image of the fuel cell, \( I_2 \) was the neutron image of the dry fuel cell, \( \Sigma_n \) and \( \Sigma_w \) are the neutron attenuation coefficients of the fuel cell body and water respectively, and \( x_n \) and \( x_w \) are the geometric thicknesses of fuel cell and water.

![Image 1](image1.png)

Fig. 10 The water distributions at flow channels of fuel cell.

The red circle area in figure 10 is the water distributions at the flow channels of the fuel cell and its grey level represents the transmission coefficient of water. Considering that the total cross section of water is 0.36/mm, the average water thickness was estimated to 1.4mm. Furthermore, figure 11 shows that the water distribution vanished gradually in 30min.

![Image 2](image2.png)

Fig. 11 The water distribution changed by time. (a)-(d) corresponded to frame 1, frame 300, frame 600, frame 900, respectively.

**Summary and conclusion**

The obtained results have demonstrated the viability of the present neutron real-time imaging station. Even at low reactor power and absence of a cold source, the present image quality was sufficient to show important features of the water dynamics in a fuel cell. The image quality will be improved dramatically after the installation
of the advanced thermal and cold neutron imaging facilities (Songbai Han et al., 2013) in the future.

Acknowledgements

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