Real Time Electromagnetic Imaging of Foreign Objects in a Heat Exchanger Tube Bundle Using a Cylinder-type Magnetic Camera

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1. Abstract

If a foreign object (FO) is present on heat exchanger (HX) tube of the nuclear power plant, it not only lowers the HX efficiency but also may lead to an accident by damaging the tube. Therefore, identifying and eliminating its presence is critical to the safe operating of nuclear power plant. In this study, we propose a method to detect FOs by imaging the electromagnetic field around a tube measured by a cylinder-type magnetic camera in real time. Three typical FO materials with different magnetic and geometric characteristics are selected and the possibility of detection and the characteristics of thee measured magnetic flux density distribution are analyzed using the proposed system.

2. Introduction

Heat exchanger (HX) in thermal or nuclear power plant is a device that deigned to exchange heat through heat transfer (mostly by conduction and convection). HXs generally have no moving parts and therefore have a long service life with little or without maintenance. However it can be exposed to four types of failure: mechanical failure, chemical corrosion, combination of mechanical and chemical damage, combination of mechanical failure & chemical corrosion, and fouling [1]. These flaws are detected through periodic non-destructive testing (NDT) and the detected flaws are repaired according to the type and degree of the flaw to prevent leakage of HX tubes during plant operation.

HX is divided into a primary side, which is an inner side, and a secondary side, which is an outer side, with the tube as a boundary. The primary side is the area where the fluid medium that receives heat from the heat source circulates, and the secondary side is the area that transfers this heat to the steam generator. If foreign objects (FOs) are present on the primary side or secondary side during construction or operation, it can cause clogging, vibration, and wear of the HX tube, thereby losing the inherent functions of the HX [2-4]. FOs on the primary side, i.e. inside of the tube, can be found relatively easily using a borescope, while the FOs on the secondary side has to be inspected along the gap of the tube bundles, so special devices such as foreign objects search and retrieval (FOSAR) tools are required [5]. However, FOSAR tools are difficult to cover the entire area of the HX tube bundles. Especially, the tube support plates (TSPs) around which fouling mainly occurs are difficult to access from the secondary side so they should be inspected through inside of the tubes (the primary side)

HX tube has a small diameter of about 12.7 ~ 22.0mm and consists of materials such as Inconel, copper alloy, stainless steel, titanium, and carbon steel. Ultrasonic or eddy current method is used to detect FOs located on the outer surface of small bore tube. One of the ultrasonic inspection methods, the internal rotary inspection system (IRIS), analyzes the ultrasound images by transmitting and receiving ultrasonic waves in a spiral manner [6]. The NDT method using IRIS is complicated because the test must be performed with the primary and secondary sides filled with water. Also, since the ultrasonic waves are reflected and absorbed by the medium, the primary & secondary side boundaries, the fouling, and the FO, the attenuation of the acoustic energy is significant, so it makes the signal analysis difficult. Motorized rotating pancake coil (MRPC) using the eddy current method measures the eddy current distribution by rotating its probe against the inner wall of the tube in the spiral direction [7]. The HX NDT using MRPC is difficult to perform the entire tube because of slow inspection speed and mechanical wear of the sensor.

The presence study propose a cylinder-type magnetic camera system that inserts sensor probe from the primary side of HX and detects FOs located on the secondary side in real time using electromagnetic field distortion [8]. Also, we report the distortion characteristics of the electromagnetic field due to the presence, size, and direction of FO of several materials.

3. Principle

In the cylinder-type magnetic camera system, an induction current is applied to the HX tube using a bobbin coil as shown in Fig. 1. When the radial direction of the tube is r, the axial direction is z, and the rotational direction is θ, the induced current in the θ direction occurs if an alternating current (AC) is applied to the bobbin coil. When there is no material that interrupts the magnetic flux flow, the magnetic flux density distribution in z direction is generated along with the induced current in the θ

direction. At this time, a ring-shape Hall sensor array having anisotropic sensitivity in the *r* direction can measure the magnetic flux density to a minimum. However, when there is a FO on the outer surface of the tube, the induced current is distorted, resulting in a change in the magnetic flux density distribution in the *r* direction and this change can be measured through the Hall sensor array. This cylinder-type Hall sensor array scans the tube electronically, and the distribution of time-varying magnetic flux density can be measured in real time. Since the measured magnetic flux density changes include the impedance and phase angle change, it is possible to extract the characteristic information such as the size of the FO.

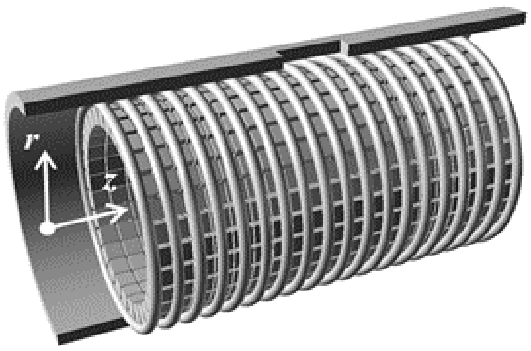

Fig. 1 A Bobbin coil and a Hall sensor array

Fig. 2 (a) shows some examples of FOs. The wrench and the grip-knife replacement blade represent typical ferromagnetic materials. The wench has a long and smooth curved shape, and the blade has a thin and sharped-edged feature. The coin has typical paramagnetic characteristics. Fig. 2 (c)-(e) shows the measurement results of the time-varying magnetic flux density distribution of individual FOs near to the TSP using a cylinder-type magnetic camera. From the imaged measurement data, large distortion occurs at both ends in the axial direction of the FOs by excitation current in the circumferential direction. More details will be presented at the International Conference on Materials and Reliability (ICMR) 2019.

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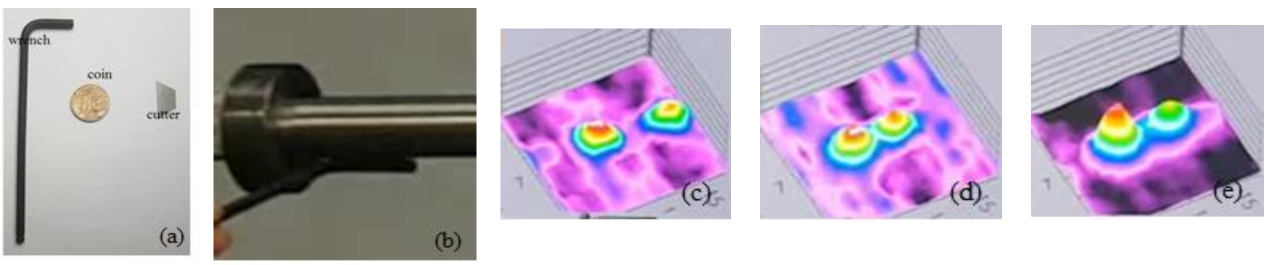

Fig. 2 Typical FOs and magnetic flux density images of the FOs; (c) wench (d) coin (e) blade