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Thermal-Fluid Characteristics of Heating Element in Rotary Heat Exchanger in Accordance with Fouling Phenomena

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Abstract**—**To decrease sulfur oxide in the flue gas from coal power plant, a flue gas de-sulfurization facility is operated. In the reactor, a chemical reaction occurs with a temperature change of the gas so that sulfur oxide is removed and cleaned air is emitted. In this process, temperature change induces a serious problem which is a cold erosion of stack. To solve this problem, the rotary heat exchanger is managed before the stack. In the heat exchanger, a heating element is equipped to increase a heat transfer area. Heat transfer and pressure loss is a big issue to improve a performance. In this research, thermal-fluid characteristics of the heating element are analyzed by computational fluid dynamics. Fouling simulation is also conducted to calculate a performance of heating element. Numerical analysis is performed on the situation where plugging phenomenon has already occurred and existed in the inlet region of the heating element. As the pressure of the rear part of the plugging decreases suddenly and the flow velocity becomes slower, it is found that the flow is gathered from both sides as it develops in the flow direction, and it is confirmed that the pressure difference due to plugging is increased.

Keywords**—**Heating element, plugging, rotary heat exchanger, thermal fluid characteristics.

I. Introduction

TO decrease sulfur oxide in a coal power plant, a flue gas desulfurization unit (FGD) is operated. In FGD system, a chemical reaction occurs with a temperature change of the flue gas and sulfur oxide is removed. After the chemical process, cleaned air which is called treated gas is emitted through a stack. In this procedure of cleaning, the temperature change induces a serious problem such as cold erosion of stack. To prevent this problem, rotary type heat exchanger is managed before the stack. In the rotary heat exchanger, a heating element is equipped to increase a heat transfer area.

Heat transfer and pressure loss are a big issue to enhance a performance in the heating element. Some research has been done to improve the thermal performance of the heating element. Stasiek et al. investigated the flow and heat transfer characteristics of the heating element experimentally and numerically [1], [2]. Vulloju experimentally analyzed the performance of heating element [3]. Their research showed that flow velocity is dominant to pressure drop and heat transfer of heating element. Cho et al. performed an experiment in a channel with ribs to investigate thermal-fluid characteristics [4]-[6]. In channel flow, rib structures can improve thermal performance as well as heat transfer coefficient. Hwang et al. have studied a heat transfer in a corrugated channel and a wavy duct by using naphthalene sublimation method [7], [8]. From their results, the geometry of the wavy duct makes a complex flow pattern.

Recently, studies on performance and prediction of rotary heat exchanger system based on single heating element analysis have been conducted. Dallaire et al. suggested the conceptual optimal structure of rotary heat exchanger with a porous medium [9]. Alhusseny and Turan show design process of rotary regenerators using a porous core [10]. They assumed the rotary heat exchanger as a porous core and its heating element as a simple geometry like a triangular prism, quadrangular prism, and circular cylinder. Lee et al. optimized heating element design in a rotary heat exchanger to improve thermal performance [11]. They suggested optimization process of heating element design in rotary heat exchanger considering decrease of pressure drop.

Despite these efforts, there are many difficulties in improving performance. A typical example is fouling of dust due to water evaporation. In the FGD, water is sprayed for the desulfurization and the treated gas is obtained through the chemical reaction. At this time, as water is evaporated by the high-temperature heating element, only the dust remains in the gas and a fouling phenomenon occurs in which particles adhere to the surface of the heating element. As the fouling gradually occurs, plugging that blocks the flow path occurs, resulting in a large differential pressure. Mbabazi and Sheer performed erosion prediction through computational analysis in an effort to see the behavior of fly ash particles in the heating element [12]. In their study, however, only the occurrence of erosion could not predict the plugging phenomenon that was blocked by fouling segment. There have been recent reports on the mechanism of corrosion occurring in rotary heat exchangers, but they still do not produce clear explanation [13]. Therefore, in this study, we analyzed the thermal-fluid characteristics of the heating element under base design and we investigated pressure drop considering the plugging phenomena of the heating element. We assumed that plugging has occurred already at the inlet region of the heating element and we used operational data of real coal power plant as a boundary condition. At last, we compared the case between original heating element which is base model and with the plugging phenomenon.

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II. Numerical Method

In this study, ANSYS CFX 17.2 is used for numerical analysis. The L-type heating element is adopted and flow regions for analysis are shown in Fig. 1. Because of plugging, the flow cannot exist to some section near the inlet area of the flow as shown in Fig. 1. The location and size of plugging are designed randomly. In the present study, the plugging has a 74 mm to the x-direction, 50 mm to the y-direction, and perfectly blocked in the z-direction. Specific size and location of plugging are shown in Fig. 1. The flow direction is the y-direction and heating element has a periodicity along to the x-direction

Fig. 2 shows a boundary condition and analysis region of the heating element. The heating element has periodicity and to simplify the calculation, periodic conditions for both sides of an element are used. The boundary condition for inlet is pressure and outlet is mass flow rate. Real operational data of coal power plant are applied as values of inlet pressure and outlet mass flow rate. Except for inlet, outlet, and periodic sides, wall conditions are applied and the walls have constant wall temperature. A working fluid is an ideal air adjusted by flue gas composition using REFPROP.

For analyzing the result, Plane A and Line A and B are classified as shown in Fig. 2. Plane A is a plane at a middle of the heating element along the z-direction. Line A is a wall line of upper plate and Line B is for a lower profile. Reynolds number of the heating element is about 4000 so that SST RANS turbulence model is used.

The Reynolds number is a non-dimensional form and is defined as (1):

$$Re = \frac{\rho u D_h}{\mu} \quad (1)$$

where ρ is a density of flow, u is a flow velocity, D_h is a hydraulic diameter of heating element, and μ is a viscosity of flow.

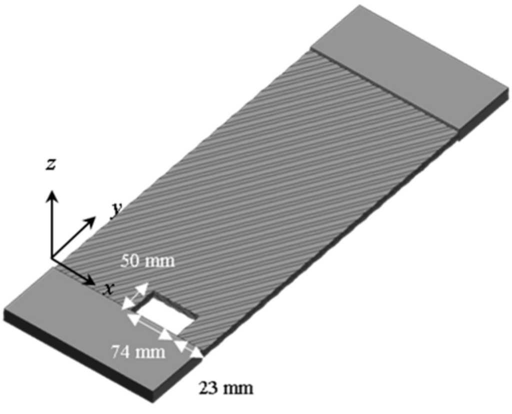

Fig. 1 Geometry of heating element and plugging

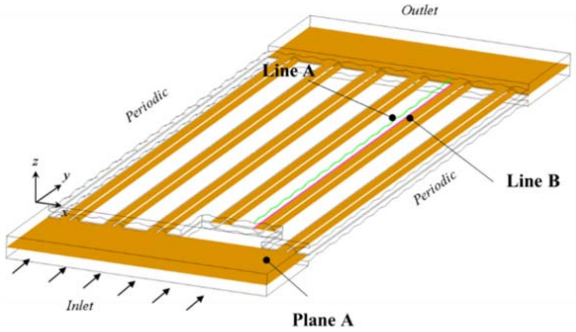

Fig. 2 Boundary condition and analysis region of heating element

III. Result and Discussions

In the base case of heating element, the gas flows from inlet to outlet along positive y-direction as shown in Fig. 3. The plate of heating element has an angle to the flow direction so that flow near the wall is shifted due to viscous effect and no-slip condition of the wall. Thus, overall velocity of right side from the center is higher than the left side. Along the x-direction, the velocity of flow decreases at same y-position. Also, the shifted flow is rotating and it increases pressure drop and turbulence intensity. There are points where the plate and the profile meet, and the flow is hit against each point. At the point, the heat transfer coefficient is higher than others because the flow is stagnated in front of the point and the flow turns around it.

In case of heating element plugging, more complicated flow characteristic occurs. Fig. 3 shows a velocity contour of the heating element with a plugging on Plane A. Along a y-direction, flow velocity decreased except for Line A and B. Maximum velocity of flow is 24 m/s and average velocity is 12 m/s. Dark color means a fast speed of flow. Right in front of plugging region, the velocity of flow is nearly zero due to stagnation. In the plugging region, a stagnation point is formed and the flow moves around the stagnation point. After plugging region, velocity is lower than other sections and nearly 0 m/s. It means that the flow after plugging region is stagnated and recirculated. This is explained in Fig. 4 expressing a contour of pressure on Plane A. Pressure of flow decreases along y-direction. However, plugging interrupts a flow so that behind it, the pressure is lower than others. Due to the pressure gradient, fluid flows from higher pressure region to lower pressure region. The lower pressure induces the gathering of main flow from both sides which have higher pressure. In this situation, the meeting point is shifted from the center to the left. The geometry of plate is the reason for shifting of the meeting point. As well as a case of heating element without plugging, an angle of the plate makes a rotating flow of gas due to viscous effect and no-slip condition. At the end of the heating element, velocity has a distribution. Especially, after the plugging region, there is the lowest velocity. In Fig. 4, at the right side of Plane A, overall pressure of the heating element is higher than left side from the center line.

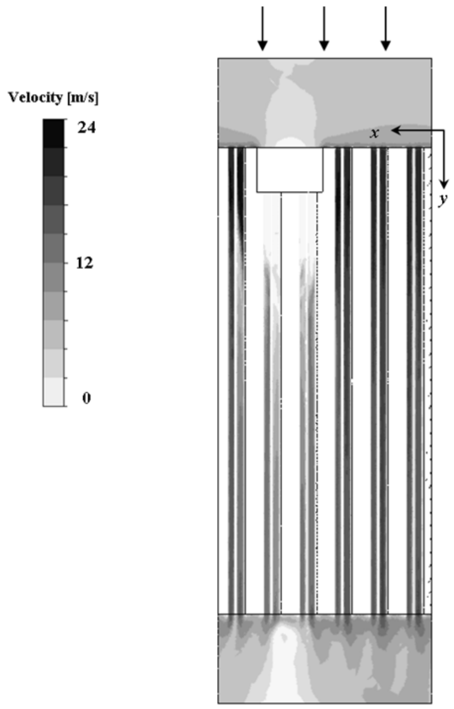

Fig. 3 Velocity distribution of heating element with plugging

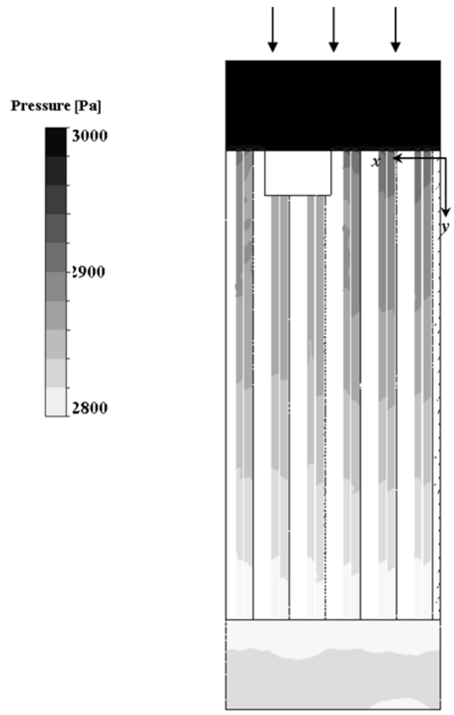

Fig. 4 Pressure distribution of heating element with plugging

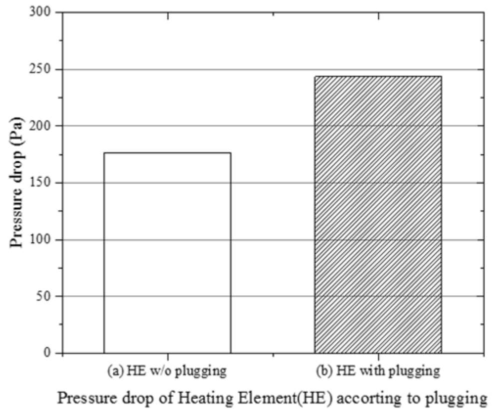

Fig. 5 Comparison of pressure drop between heating element w/o plugging and with plugging

Fig. 5 is a graph comparing the pressure drop of heating element without plugging and a heating element with plugging. For the case of heating element without plugging, the pressure drop is about 176 Pa while the case of heating element with plugging shows 243 Pa. Due to the shape of the plate with a tilted pattern, after the point where plugging occurs, the flow does not have a periodicity and is merged by the pressure gradient. This result indicates that a small plugging size can aggravate the loss.

IV. Conclusion

In the present study, thermal-fluid characteristics of heating element considering the plugging phenomenon in a rotary heat exchanger are analyzed. The gas flows along the y-direction and has rotation induced by the geometry of wall. The rotating flow increases turbulence intensity and makes higher heat transfer coefficient. As shown in Fig. 3, when plugging occurs perfectly, flow has lower velocity due to drastic pressure loss. The pressure loss is induced by recirculation of flow after the plugging. This loss can increase the overall pressure drop about 38% as shown in Fig. 5. The size of plugging is small compared to the overall fluid volume. Therefore, plugging is dominant in pressure drop.

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