Research on the detection of fouling and slagging in cold state based on capacitance principle

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Abstract. Aiming at the requirement of on-line monitoring for the fouling and slagging in the syngas cooler of coal gasifier, this paper proposes a detection method of deposition thickness based on the capacitance principle. A capacitance measurement rig for deposition detection is built to conduct a cold state simulation experiment. The coal ash and syrup are selected as medium to simulate the fouling and slagging in cold state. Two kinds of electrodes including single-electrode and double-electrode probes are used to measure the capacitance of deposition. The results show that the measured capacitance increases linearly with the increase of the deposition thickness for all the cases. The linear correlations between the capacitance value and the deposition thickness are obtained for ash and syrup under two kinds of electrodes, respectively. Verification tests show that the predicted deposition thicknesses by employing the linear correlations are basically consistent with the real thickness, and the maximum error is 5.15%. The detection error with single-electrode is less than that with double-electrode due to more deposition amount between two electrodes.

1. Introduction
Coal gasification is one of the main methods on high efficient and clean utilization of coal resources. The syngas from gasification chamber has a high temperature about 1200 ~ 1600 °C. The sensible heat of high temperature syngas generally accounts for more than 15% of the total heat in coal [1]. Therefore, the waste heat recovery for the high temperature syngas can effectively improve the overall efficiency of coal gasification. In current gasification systems, the syngas cooler is the most commonly used equipment to recovery the syngas heat, including radiant syngas cooler (RSC) and convection syngas cooler (CSC) [2, 3]. RSC and CSC are used to recovery the waste heat of high temperature syngas (>800°C) and low temperature syngas (<800°C), respectively. They have the similar functions as radiant heat exchanger and convection heat exchanger in utility boilers.

However, compared with high temperature gas in utility boilers, the syngas of coal gasification contains a large number of slag and ash particles, and there is no internal heat source in syngas cooler. It results in that the fouling and slagging on the heating surface of syngas cooler are more prominent. Generally, the slagging occurs in RSC when the molten slags in the high temperature syngas contact with the heating surface and then stick on it. The fouling happens much in CSC where the fly ash particles in the low temperature syngas deposit on the heating surface. The fouling and slagging weaken the heat transfer of syngas cooler and decrease the unit efficiency. Excessive fouling and slagging can lead to the ash or slag blocking the syngas passage, and even unit shutdown.
accident [4, 5]. Therefore, on-line monitoring about ash and slag deposition on the heating surface of syngas cooler is very necessary to ensure the safe operation of gasification unit. In most present gasifiers, the fouling and slagging in syngas cooler is indirectly detected based on the heat transfer parameters such as heat flux, furnace temperature and syngas outlet temperature. However, due to the complex environment with high temperature, high pressure, and gas/liquid/solid multiphase flow in the syngas cooler, these indirect monitoring methods are unreliable to detect the fouling and slagging in practical process.

In recent years, some novel approaches are developed to detect the pollutant deposition in heat exchangers, such as the sonic wave, infrared visualization and electrical principle [6]. These new detection methods have been the research focuses, especially in food industry [7, 8]. Among, the electrical detection principle is that, one or more electrodes is installed on the surface of heat exchanger. Thus, the fouling condition can be detected by monitoring the electrical parameters (e.g. resistance, capacitance), which will be changed when the fouling occurring on the heat transfer surface. Because the measuring electrode directly contacts with the pollutant (namely, an in-situ monitoring), this method has the advantages of high accuracy, sensitivity, and little influence from environment.

Considering the complex and changeable internal environment in syngas cooler of gasifier, the electrical monitoring for the fouling and slagging in syngas cooler has a potential research value. Based on this, the present study builds a deposition detection rig with capacitance principle. A cold state simulation experiment is carried out to study the relation of measured capacitance with the deposition thickness.

2. Detection principle of capacitive

The detection of deposition thickness in current study is based on the coaxial capacitor principle [9], as shown in Figure 1. A metal probe is placed in the center of container, where there are some measured mediums being deposited. Thus, the metal probe, the medium, and the container wall constitute a capacitor. The metal probe and the container wall are as the two electrode of the capacitor. The capacitance between the two electrodes can be written as:

$$ C = C_1 + C_2 + C_3 $$

Where, $C$ is the total capacitance, $C_1$ is the equivalent stray capacitance, $C_2$ is the capacitance caused by air between two electrodes, and $C_3$ is the capacitance caused by the measured medium.

$$ C_2 = \frac{2\pi\varepsilon_0 (H_0 - H_1)}{\ln(D/d)} $$

$$ C_3 = \frac{2\pi\varepsilon_1 H_1}{\ln(D/d)} $$

Where, $\varepsilon_0$ and $\varepsilon_1$ are the dielectric constants of air and measured medium, respectively. $H_0$ is the
height of container and $H_1$ is the thickness of measured medium. $D$ and $d$ are the diameters of container and metal probe, respectively.

Substituting Eqs. (2) and (3) into Eq. (1), the total capacitance can be written as:

$$C_i = C_0 + \frac{2\pi e_0 H_0}{\ln(D/d)} + \frac{2\pi (e_i - e_0) H_1}{\ln(D/d)}$$

$$C_i = \frac{2\pi e_i H_1}{\ln(D/d)}$$

Therefore, Eq. (4) can be abbreviated as:

$$C_i = C_0 + KH_i$$

Where, $C_0$ and $K$ are two constants, which are related to the dielectric constant of the medium and the structure of the container. It can be seen that the measured total capacitance $C_i$ is correlated linearly with the deposition thickness $H_1$ of the medium. Therefore, if the constants of $C_0$ and $K$ can be determined, the thickness of the measured medium can be obtained according to the measured capacitance based on the Eq. (5).

### 3. Experimental apparatus

#### 3.1 Test section

Figure 2 shows the diagram of the test section in the experimental apparatus. The test section consists of the electrode probe and the deposition chamber. The deposition chamber adopts a separated structure, which contains a stainless open cavity, a stainless board as the bottom, and an acrylic board as the top. The center of bottom board is drilled with a threaded holes of 20mm to install the electrode probe. The top board is cut with a square hole to add the medium into chamber. The bottom and top boards are clamped with the screws to avoid the measured medium to leak.

#### 3.2 Measured mediums

The fouling occurring in the CSC is mainly caused by the fly ash particles entrained in syngas, therefore, the current experiment selects the coal ash [Figure 3 (a)] as medium to simulate the fouling in cold state.

![Mediums](image)

(a) Coal ash (b) Potential substitutes for slag

Figure 3. Mediums.

The slagging in the RSC is happened when the molten slags contact the water wall, solidify and
stick to the wall. Since it is hard to realize the high temperature environment (>1000°C) of RSC under laboratory conditions, some substitutes are selected to simulate the slagging process in the open literatures, such as syrup and paraffin [11,12]. Based on these, this study chooses the three kinds mediums of syrup, paraffin, rosin as the potential substitutes of slag, as shown in Figure 3 (b). Among, the slag is obtained from the gasifier in Yangmei Fengxi Fertilizer Industry.

Due to the dielectric constant being a key parameter to determinate the capacitance of measured medium, the dielectric constants of three substitutes and the real slag are measured by employing a broadband dielectric spectrometers (Model: Novocontrol GmbH, Germany). The test data are shown in Figure 4. It is shown that the dielectric constant of slag decreases with the increase of test frequency. The dielectric constant of slag is obviously higher than that of other mediums in the low testing frequency range (< 100 kHz). However in the high frequency range (> 100 kHz), the dielectric constant of syrup is basically same to that of slag, while the dielectric constants of paraffin and rosin are obviously smaller. Therefore, this study selects the syrup as an alternative medium to simulate the slag in cold state.

![Figure 4. Dielectric constants of mediums.](image)

3.3 Test electrode
Two kinds of electrode probes are used in this experiment, including the single-electrode probe and the double-electrode probe, as shown in Figure 5. When using the single-electrode probe for testing, the probe and cavity wall are used as two electrodes of the capacitor (as shown in Figure 2). While using the double-electrode probe, two probes are used as two electrodes of capacitor. The capacitance value for the capacitor is recorded by a high precision digital electric bridge (Model: Victor-4080C, China). Figure 6 shows the photograph of the experimental apparatus.

![Figure 5. Electrode probe.](image)

![Figure 6. Experimental apparatus.](image)

During the test process for ash deposition, the coal ash is firstly naturally deposited in the test chamber, then a spatula is used to shave the ash surface to be flat, and the capacitance of ash
deposition is recorded. For the test of syrup deposition, the syrup is firstly heated to 180 °C for melting, and the molten syrup is deposited in the test chamber. When the molten syrup solidifies and its temperature decreases to the ambient temperature, the capacitance is measured. The ambient temperature is maintained at 25 ~ 26 °C by air conditioning during all test processes.

4. Results and discussion

4.1 Effect of test frequency on capacitance value

Figures 7 (a) and (b) show the effects of test frequency on capacitance value for the single-electrode probe, with ash deposition and syrup deposition, respectively. It can be seen that, under a fixed frequency, the test capacitance increases with the deposition thickness of ash/syrup increasing. For a given deposition thickness, the capacitance value has a fluctuant variation with the test frequency changing, and the variation trends are basically consistent for different deposition thicknesses. Figures 8 (a) and (b) show the effects of test frequency for the double-electrode probe. The phenomena is consistent with that of single-electrode test.

4.2 Effect of deposition thickness on capacitance value

According to the results in Figure 4, the dielectric constant of syrup is basically consistent to that of slag at high frequencies. Meanwhile, considering that the frequency bands of capacitive sensors in industrial applications are mostly near 100kHz [13,14], this paper chooses 100 kHz as the test frequency to study the relationship between the deposition thickness of medium and the measured
4.2.1 Ash deposition

Figure 9 displays the variations of test capacitance with ash deposition thickness varying, under the single-electrode probe and double-electrode probe, respectively. It shows that with the increase of the ash deposition thickness, the measured capacitance value increases gradually. Especially, the capacitance value has a significant linear relation with the deposition thickness. This is consistent with the linear law presented in Eq. (5). By fitting the test data, the linear correlations between the capacitance and the ash deposition thickness are obtained as follows: $C_t=0.033H_1+9.309$ for the case of single-electrode probe, $C_t=0.033H_1+4.069$ for the case of double-electrode probe. As can be noticed, the slopes of the two correlations are same, but the intercept for the single-electrode is about twice than that for double-electrode. It can be attributed to the different ash content between the two electrodes for two kinds of test electrodes. Under the same ash deposition thickness, the amount of ash between single-electrode probe and the cavity wall (as the other electrode) is much larger than that between the two probes with double-electrode probe.

![Figure 9. Variations of test capacitance with ash deposition thickness varying.](image)

4.2.2 Syrup deposition

Figure 10 displays the variations of test capacitance with syrup deposition thickness varying. There is also a linear relationship between the test capacitance and the syrup deposition thickness. The linear correlations for single-electrode and double-electrode are $C_t=0.103H_1+11.943$ and $C_t=0.093H_1+3.272$, respectively. The slopes of two correlations are similar, but the intercept of former is obviously larger than that of latter.

![Figure 10. Variations of test capacitance with syrup deposition thickness varying.](image)
4.3 Verification tests

Based on the linear correlations above, the verification tests are conducted as follows. By setting random deposition thickness of ash/syrup and reading the measured capacitance value, thus, the predicted deposition thickness may be obtained by employing the above linear correlations. Tables 1-2 display the comparisons of the predicted deposition thickness and the real thickness. The real thickness is obtained by using a vernier caliper.

| Case                      | Single-electrode | Double-electrode |
|---------------------------|------------------|------------------|
| Capacitance value /pF     | 10.205           | 27.30            |
| Predicted thickness /mm   | 27.9             | 58.21            |
| Real thickness /mm        | 27.9             | 58.21            |
| Relative error            | 2.14%            | 68.21            |

Table 1. Comparisons for ash deposition with single-electrode and double-electrode.

| Case                      | Single-electrode | Double-electrode |
|---------------------------|------------------|------------------|
| Capacitance value /pF     | 13.963           | 19.58            |
| Predicted thickness /mm   | 19.9             | 34.5             |
| Real thickness /mm        | 19.9             | 34.5             |
| Relative error            | 1.60%            | 57.5             |

Table 2. Comparisons for syrup deposition with single-electrode and double-electrode.

As seen from the data in the tables, the predicted deposition thicknesses by applying the linear correlations agree well with the real thicknesses. The maximum errors (absolute value) for ash and syrup deposition with the single-electrode are 2.14% and 3.54%, respectively. These are lower than those with the double-electrode, which are 3.48% and 5.15%, respectively. It can be explained that the capacitance measured by the single-electrode is decided by the deposition between the probe and the cavity wall, while the capacitance for double-electrode is decided by the deposition between two probes. The deposition amount of former is much larger than that of latter. As a result, the capacitance for the double-electrode is lower and the maximum error is larger, compared to the single-electrode. However, the double-electrode has an advantage that it does not need to use the cavity wall as an electrode of capacitor. It means that the double-electrode is more flexible to install in practical application and is not limited by the shape and material of the cavity.

5. Conclusion

This paper conducts an experiment study on the detection of deposition in cold state based on capacitance principle. The coal ash and syrup are selected as mediums to simulate the fly ash and slag. Two kinds of electrode probes are used to measure the capacitance value. The results show that the syrup has a similar dielectric constant with the real slag in high frequency range (> 100 kHz). The capacitance values fluctuate with the test frequency changing, under a given deposition thickness. The capacitance increases linearly with the deposition thickness increasing. The linear fitting correlations of ash deposition by single/double-electrode are \( C_t = 0.033H_t + 9.309 \) and \( C_t = 0.033H_t + 4.069 \), respectively; the correlations of syrup are \( C_t = 0.103H_t + 11.943 \) and \( C_t = 0.093H_t + 3.272 \), respectively.
Verification tests show that the predicted deposition thickness by applying the above correlations is basically consistent with the real thickness, and the maximum error is 5.15% for the current cases. The prediction error of the deposition thickness by single-electrode is less than that by double-electrode. These findings can provide beneficial guidance for the capacitance detection to be applied for the on-line monitoring of the fouling and slagging in the syngas cooler.

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