Effect of Impact Velocity on Liquid Droplet Impingement Erosion of Carbon Steels and a Stainless Steel using Spray Nozzle

INTRODUCTION

Liquid droplet impingement (LDI) erosion has become increasingly a pipe wall thinning problem for piping systems and one of the main factors causing vapor leaking problem in power plants. Liquid droplet impingement erosion can easily occur at downstream of pipe bend or corner parts of the piping system and also where the water flow of the pipe is changing direction. Two common factors causing damage to piping system is breakage of oxide film and removal of base metal. Researchers related to LDI erosion subject to material used in producing windows for airplane such as plastic and glass has been carried out in the past. However, existing experiment data regarding wall thinning problem of piping system, particularly research related to flow dependency of piping material are considerably few. Hattori and Hayakawa investigated the effect of impact velocity on liquid droplet impingement erosion of carbon steels and a stainless steel. It was found that erosion rate increases with the 6th power of impact velocity for S15C and STPA24, and the 7th power for SUS304, and the threshold velocity below which erosion rate is negligibly small was found 80m/s for S15C, 90m/s for STPA24 and 120m/s for SUS304. However, the average size of droplet diameter produced from jet nozzle in this experiment is about 400μm, which is higher compared to average droplet size reported in piping system between 10-30μm.

In this study, we used a spray nozzle, an apparatus capable of jetting out a relatively small droplet and discussed the effect of impact velocity on liquid droplet impingement erosion of carbon steels and stainless steels.

MATERIALS AND EXPERIMENTAL PROCEDURE

The liquid droplet impingement tests were carried out by using a cavitating liquid jet chamber specified in the ASTM G134-95 standard shown in Fig.1 and a spray nozzle (high pressure fan shape nozzle 1/8MVNP2525S303 made by IKEUCHI Co., LTD.). The Sauter average droplet size from Fujisawa Laboratory of Niigata University is about 60μm. The temperature of tap water is kept at 20 degree Celsius. The downstream pressure (absolute pressure) is 0.1MPa and upstream pressure is controlled ranging from 10 to 35MPa. The distance between pressure at nozzle entry (downstream pressure) and nozzle exit (upstream pressure) determined the flow velocity directly after jet out from spray nozzle.

Fig.1 Test chamber

Table 1 Chemical composition of test material

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>V</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Cr</th>
<th>Al</th>
<th>Fe</th>
<th>Ti</th>
<th>Mo</th>
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<tbody>
<tr>
<td>Al</td>
<td>-</td>
<td>0.06</td>
<td>-</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td>S15C (STPG370)</td>
<td>0.16</td>
<td>0.21</td>
<td>0.45</td>
<td>-</td>
<td>0.01</td>
<td>0.016</td>
<td>0.01</td>
<td>0.08</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SUS304</td>
<td>0.06</td>
<td>0.20</td>
<td>1.67</td>
<td>-</td>
<td>0.043</td>
<td>0.027</td>
<td>-</td>
<td>8.00</td>
<td>18.73</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>STPA24</td>
<td>0.12</td>
<td>0.35</td>
<td>0.47</td>
<td>0.002</td>
<td>0.012</td>
<td>0.004</td>
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<td>2.12</td>
<td>0.002</td>
<td>0.001</td>
<td>0.93</td>
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Table 2 Mechanical properties of test material

<table>
<thead>
<tr>
<th>Material</th>
<th>Density kg/m³</th>
<th>Tensile strength MPa</th>
<th>Vickers hardness HVD0.2</th>
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<tr>
<td>Al</td>
<td>2.71×10³</td>
<td>95</td>
<td>38</td>
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<tr>
<td>S15C (STPG370)</td>
<td>2.81×10³</td>
<td>441</td>
<td>145</td>
</tr>
<tr>
<td>SUS304</td>
<td>7.93×10³</td>
<td>792</td>
<td>171</td>
</tr>
<tr>
<td>STPA24</td>
<td>7.72×10³</td>
<td>630</td>
<td>216</td>
</tr>
</tbody>
</table>

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The experiment was performed at a stand-off distance (distance between nozzle and test specimen) of 30mm determined using pure aluminum as test specimen. The test specimen surface was polished to make a smooth surface before performing a test. After each test time, the test specimen was first washed with ultrasonic cleaner. Secondly, the weight and surface profiles of test specimen were measured. The apparatus specialized in measuring surface of test specimen is Keyence high accuracy surface scanning system KS1100 and J-G015.

S15C (carbon steel equivalent to carbon pipe steel STPG370), SUS304 (stainless steel equivalent to stainless pipe steel) and STPA24 (alloy pipe steel) were used for erosion tests. Chemical composition and mechanical properties were shown in Tables 1 and 2 respectively. An example for the shape of test specimen and after performing a test was shown in Figs.2 and 3 respectively.

**EXPERIMENTAL RESULTS**

**Mass loss**

Fig.4 shows mass loss-time curves of test specimen SUS304. These curves show the incubation, the acceleration and the maximum rate stage. In comparison, exposure time for cumulative mass loss to reach 10mg of each flow velocity was about 2.5hrs at 260m/s, about 7hrs at 240m/s, about 16hrs at 220m/s and about 50hrs at 200m/s. Each flow velocity of 180m/s, 170m/s, 160m/s and 150m/s did not reach cumulative mass loss of 10mg after 100hrs of exposure time and no erosion occurs at 170m/s, 160m/s and 150m/s. Incubation period becomes longer with the decreased flow velocity.

**Maximum depth of erosion**

There are many other causes resulted in mass loss of material other than liquid droplet impingement. Furthermore, in pipe wall thinning problem, rather than average wall thinning value, it is important to investigate maximum depth value of wall thinning. So in addition to mass loss, liquid droplet impingement erosion was evaluated using maximum depth of erosion (MaxDE). Fig.6 shows the definition of MaxDE. On the left side (a) is the surface profile of test specimen SUS304 with the flow velocity of 260m/s after 5 hours using at high accuracy surface measurement system. The photograph was taken in 3 dimensional figures. From (a), color was added with the difference in height. An orange color equals to surface of the test specimen and as the blue color darken turning into black, the depth damage caused by erosion is greater. Then one section in which maximum depth is directly orthogonal to surface was selected and shows in (b). The cross section between surface of the test specimen and deepest depth is calculated and the measured value is the definition of MaxDE. In (b), the MaxDE of this test specimen is 564µm.
Fig. 6 Definition of MaxDE

Fig. 7 Erosion process of test specimen (SUS304, 220m/s)

Fig. 7 shows one example of erosion process. The test specimen used was SUS304 at a flow velocity of 220m/s. There is a figure of 5 different exposure times starting from top to bottom. The first is the original surface profile at 0 hour. Second is the surface profile after 10 hours in which the surface started to erode and causing damage. Then after 15 hours, 20hours and 25 hours in consequence the damage to surface is deepened and measurement value of MaxDE is higher. It can be seen that the shape of the damage forming a V shape. It is considered the liquid droplet impinge directly proportional to surface of the test specimen. The MaxDE of the each exposure time is 0µm at 0 hour, 216µm at 10 hours, 322µm at 15 hours, 450µm at 20 hours and 511µm at 25 hours.

Fig. 8 shows the MaxDE-time curves for each of the materials. Fig 8.(a) shows the MaxDE curves of S15C. The incubation period is one to twenty-five hours, with the tendency to become longer with the decreased impact velocity. There is no erosion occurs at 150m/s. Fig 8(b) shows the MaxDE curves of SUS304. The behavior of the MaxDE curves of SUS304 is similar to that of S15C. The flow velocity in which erosion did not occur however, is slightly higher at 170m/s. Fig 8(c) shows the MaxDE curves of STPA24 with similar behavior to that of S15C and SUS304. Erosion did not occur at 180m/s.

Fig. 9 shows the flow velocity dependency of maximum depth of erosion rate (MaxDER) for each material. The MaxDER is defined as the MaxDE in the maximum erosion rate stage divided by the exposure time interval taken from the highest 3 point stages of MaxDE for each line shows in Fig 8 beforehand. The MaxDER increases in proportion with the 7.3th power of impact velocity for S15C, the 7.4th for SUS304 and 7.5th for STPA24 respectively. The exponent of impact velocity is similar for each material. The threshold impact velocity, below which erosion rate is negligible or zero for these materials are 150m/s for S15C, 170m/s for SUS304 and 180m/s for STPA24.

Fig. 10 shows the relation between threshold impact velocity and Vickers hardness. Vickers hardness for each material is 145 for S15C, 171 for SUS304 and 214 for STPA24. Threshold impact velocity for test using Jet nozzle is 80m/s for S15C, 120m/s for SUS304 and 90m/s for STPA24. The differences between threshold impact
velocity values using jet nozzle and spray nozzle is discussed. For spray nozzle, the threshold impact velocity increases with the higher Vickers hardness. However, the higher Vickers hardness for STPA24 shows a lower threshold impact velocity than SUS304 with the lower Vickers hardness.

In comparison, the margin between threshold impact velocity of SUS304 and STPA24 is lower in the test carried out using spray nozzle than that of jet nozzle. In formula of impact load, stress is in proportion to that of flow velocity, so the vertical line of threshold impact velocity is equivalent to that of stress. Phenomenon in which threshold impact value of STPA24 was lower using jet nozzle can be explained using a relation between tensile strength and fatigue strength shown in Fig.11 [1]. For the test carried out in air environment, the fatigue strength increased in accordance together with the tensile strength. However, when carried out in water environment, at one point, the fatigue strength is increasing at a very slow rate. The inclination is similar to that of STPA24 and S15C which can suffer from corrosion in water environment. SUS304 is similar to inclination in air environment because this material is stainless, which does not readily corroded.

The lower margin between SUS304 and STPA24 for the test carried out using jet nozzle and spray nozzle is explained in S-N curves shown in Fig.12 [2]. The vertical line is stress amplitude (σa) and horizontal line is number of stress cycles to failure (Nf). Stress is in proportion to that of flow velocity, so the higher stress amplitude means the higher flow velocity. The test carried out in air environment shows a small decreased in stress amplitude with the increased number of stress cycles to failure. However, in deionized water environment, the stress amplitude is decreased intensely with the increased number of stress cycles to failure. This result shows that for the test carried out in water environment, higher amplitude has smaller damage and influence from water also small. Same rules can be applied to test carried out for liquid droplet impingement test where higher threshold impact velocity has smaller corrosion influence from water.

CONCLUSIONS

The results from investigation of the effect of impact velocity on liquid droplet impingement erosion of carbon steels and stainless steels are summarized as follows:

1. The MaxDER increases in proportion with the 7.3th power of impact velocity for S15C, the 7.4th for SUS304 and 7.5th for STPA24 respectively
2. The threshold impact velocity, below which erosion rate is negligible or zero for these materials are 150m/s for S15C, 170m/s for SUS304 and 180m/s for STPA24
3. The threshold impact velocity increased with increased Vickers hardness
4. In comparison, the margin between threshold impact velocity of SUS304 and STPA24 is lower in the test carried out using spray nozzle than that of jet nozzle because the influence from corrosion in water is lower at higher threshold impact velocity

References