Study on microdroplet diameter enlargement for enhancement of moisture separation efficiency

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Abstract
Wave-shaped vanes are widely used in various power and energy systems for improved efficiency and prevention of droplet erosion. The vanes consist of wave-shaped parallel plates with pockets. As wet steam flows through the wave-shaped path, heavier droplets are thrown to the outside and captured in the pockets while frequently changing direction. However, microscale droplets are difficult to completely catch since they flow straight with the steam and are carried over through the wave-shaped vanes. Accordingly, we previously investigated installing a wire mesh at the inlet of the wave-shaped vanes to enhance the droplet capture efficiency by enlarging the microdroplets. In the present study, we examined the effect of the wire mesh configuration on enlarging the microdroplet size through air–water experiments. Droplet diameters were measured by a real-time image processing system consisting of a CCD camera and pulsed laser light source. The results showed that the droplet diameter distribution largely depended on the wire mesh configuration. We evaluated the mass flow ratio for droplets with a diameter smaller than the threshold diameter. The ratio was smallest in the case of the six-layer configuration of 0.65 mm diameter compared with two other cases, 0.19 and 0.80 mm, whereas the pressure loss was largest in the case of 0.19 mm. We conducted flow visualization at the outlet of the wire mesh using a high-speed camera. The visualization results showed that a liquid film had formed over the layered wire mesh and the surface wave of the liquid film on the last layer induced the detachment of enlarged droplets from the liquid film.

Keywords: Moisture separation, Microdroplet, Droplet enlargement, Wire mesh, Pressure loss

1. Introduction

In a nuclear power plant (NPP) using a light water reactor (LWR), the moisture separator reheater (MSR) is one of the main components of the turbine island. The MSR is placed between the high-pressure steam turbine and the low-pressure steam turbine on the main steam line. Wet steam coming from the nuclear reactor is more than 10 wt% moisture. Most of this moisture is removed by wave-shaped mist eliminators in the MSR to reduce the moisture loss, and the wet steam is reheated in the MSR to increase the thermal efficiency of the NPP. Droplets included in the wet steam from the reactor are captured in the wave-shaped vanes, except for some small-diameter droplets that pass through the eliminators as shown in Fig. 1. In other words, the wave-shaped vanes have a lower limit for the droplet diameter, $D_{th}$, that can be captured. As a result, droplets of less than about 1 wt% moisture are carried over the vanes and the moisture is evaporated by the reheater. In this process, the phase change enthalpy is consumed. To save this energy, we have been developing a high-performance moisture separator using layered wire mesh set at the inlet of the wave-shaped vanes. The goal is to increase the moisture removal efficiency at wave-shaped vanes by making the droplet diameter larger than $D_{th}$.

Regarding droplet collection by wires, the inertial parameter, which depends on the droplet size, air speed and wire diameter, affects the droplet collection efficiency (Langmuir and Blodgett, 1946). The table of collection efficiency
versus inertial parameter (Brun et al., 1955) has been used in practice. The theoretical collection efficiency of the wire mesh was constructed based on the theory for a single wire. The theoretical collection efficiency of a one-layer wire mesh was given as the product of the theoretical collection efficiency of one wire and the relative projected area of the one-layer wire mesh (Bürkhorz et al., 1972). Furthermore, the theoretical collection efficiency of a multi-layer wire mesh was expressed as a function of the total thickness of the layered mesh (Bradie et al., 1969; Sugita et al., 1982).

However, as these evaluation methods were developed for droplet collection as a demister, they could not be directly applied for our intended purpose. In using layered wire mesh to enlarge the droplets, it is necessary to clarify the dependency of the droplet enlargement characteristics on the layered wire mesh configuration, e.g., wire diameter, size of opening and number of layers. In the present work, the diameters of droplets at the outlet of the layered wire mesh were measured to clarify the moisture reduction effect. Plain fabric wire mesh was used as the most basic shape. Figure 2 shows an example illustration of plain fabric wire mesh. The parametric effect of the wire diameter and the number of layers were examined by means of an air–water two-phase flow experiment.

![Droplet](image)

Fig. 1 Diameter limitation for droplet capture in the wave-shaped vane. A droplet with a diameter less than $D_{th}$ is carried over.

**NOMENCLATURE**

- $d$: Wire diameter (m)
- $d_i$: Droplet diameter of i-th droplet (m)
- $D_{th}$: Threshold droplet diameter (m)
- $F$: Mass frequency (%)
- $G$: Mass flow (kg/s)
- $L_n$: Number of layers of wire mesh (-)
- $LWR$: Light water reactor
- $m_i$: Mass of i-th droplet (kg)
- $M$: Total mass of measured droplets (kg)
- $MSR$: Moisture separator re heater
- $NPP$: Nuclear power plant
- $p$: Pressure (Pa)
- $U$: Mean velocity in bulk flow (m/s)
- $\pi$: Circular constant (-)
- $\Delta d$: Width of histogram (m)
- $\Delta m_i$: Subtotal of mass in $\Delta d$ (kg)
- $\Delta t$: Sampling time (s)
- $\zeta$: Pressure loss coefficient (-)
- $\rho$: Density (kg/m$^3$)
- $x$: Mass flow ratio of gas phase (-)
2. Experiments
2.1 Experimental apparatus

Figure 3 shows the schematics of the air–water experimental apparatus (Yamamoto et al., 2013; Ishikawa et al., 2014). The test section was made of a transparent PVC pipe and the diameter of the test section was 100 mm. Compressed air was supplied to the test section after adjusting the flow rate by a flow control valve. Water was supplied to a spray nozzle at a flow rate adjusted by a control valve. The water was sprayed from a spray nozzle and dispersed flow was formed in the test section. Wire mesh was installed at the downstream of the spray nozzle in the test section. The air flow rate was measured by a rotameter and the water flow rate was measured by a volumetric flow meter. The measurement error for the air and water flow rate was ±2.5% and ±2%, respectively.

At the downstream of the wire mesh, two transparent glass windows were installed on two facing surfaces of the pipe to observe re-entrained droplets and acquire photos. A YAG laser was used to capture images of the droplets. The laser beam from a single-pulsed Nd:YAG laser was converted to visible light by a diffuser lens. The flow field was irradiated by the visible light from one side of the windows. From the other side of the windows, digital images of the droplets were taken by a CCD camera with an optical lens and the images were stored on a computer. The field of view captured by the CCD camera was 3×3 mm and the depth of field was approximately 50 μm. The position at which the visualization images were captured was set at approximately 70 mm from the outlet of the wire mesh on the center axis of the test section. Following the experiments, the droplet diameter distribution was obtained by the Oxford Lasers VisiSize Ver. 6 image processing system.

Pressure measurement taps were set at the upstream and downstream of the wire mesh to obtain the differential pressure loss of the wire mesh. The differential pressure was measured using a U-tube manometer with a measurement error of ±10 Pa.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Equipment for droplet size measurement.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Model, Specifications</td>
</tr>
<tr>
<td>Optical lens</td>
<td>Nikon Micro-Nikkor 200 mm f/4</td>
</tr>
<tr>
<td>CCD camera</td>
<td>Oxford Lasers MP II</td>
</tr>
<tr>
<td></td>
<td>Number of pixels: 1600×1200; Pixel size: 7.4 μm</td>
</tr>
<tr>
<td>Image processing system</td>
<td>Oxford Lasers VisiSize Ver. 6</td>
</tr>
</tbody>
</table>
Fig. 3 Schematics of the air–water experimental apparatus. Water was sprayed from the spray nozzle and dispersed flow was formed in the pipe. Wire mesh was installed at the downstream of the spray nozzle in the pipe. Two transparent glass windows were installed at the downstream of the wire mesh for capturing images of the droplets.

2.2 Flow conditions

In an actual MSR of the LWR, steam that contains droplets of more than 10 wt% flows into the inlet of the moisture separator under high pressure and saturated conditions. In the present experiment, steam with droplets was simulated by the air and water under 0.04 MPa (gage) at ambient temperature. Here, the bulk flow moisture was set at 15–16 wt%, which was almost the same value as the actual conditions. The flow conditions are summarized in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section</td>
<td>Pressure 0.04 MPa (gage)</td>
</tr>
<tr>
<td></td>
<td>Temperature ambient temperature</td>
</tr>
<tr>
<td>Inlet air</td>
<td>Volumetric flow 95 m³/h</td>
</tr>
<tr>
<td>Spray water</td>
<td>Pressure 0.22 MPa (abs.)</td>
</tr>
<tr>
<td></td>
<td>Volumetric flow 0.331–0.358 L/min</td>
</tr>
<tr>
<td>Bulk flow moisture</td>
<td>15–16 wt%</td>
</tr>
</tbody>
</table>

2.3 Test wire mesh

The test wire mesh consisted of multiple layers of plain fabric wire mesh joined to each other. Table 3 shows the specifications of the wire mesh. The design parameters for plain fabric wire mesh are the wire diameter, opening size, aperture ratio and number of layers. We examined the parameters using the knowledge gained from past studies (Brun et al., 1955; Sugita et al., 1982). Based on this knowledge, we decided to change the wire diameter and number of layers under an almost constant aperture ratio of 50% as a geometry parameter, as shown in Table 3. Figure 4 shows example photos of the test wire mesh, where $d$ is the wire diameter and $L_n$ is the number of layers. In layering the wire mesh with diameters of 0.65 and 0.80 mm, we set each layer by shifting it half a pitch as shown in Fig. 4. In the case of wire mesh with a diameter of 0.19 mm, we set each layer in a random manner since it was difficult to control the pitch because of
the small opening.

Table 3  Specifications of wire mesh.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Wire diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.19 mm</td>
</tr>
<tr>
<td>Aperture ratio</td>
<td>47%</td>
</tr>
<tr>
<td>Opening</td>
<td>0.435 mm</td>
</tr>
</tbody>
</table>

Fig. 4 Example photos of layered wire mesh ($d = 0.65$ mm, $L_n = 6$). The test wire mesh consisted of multiple layers of plain fabric wire mesh joined to each other.

3. Results and discussion
3.1 Characteristics of droplet diameter distribution

Figure 5 shows example images of the droplets downstream from the wire mesh, which were captured by the CCD camera in the case of $d = 0.65$ mm with various layers. To obtain basic data on droplets under conditions without the wire mesh, a no-mesh case test was also conducted. In the case of single-layer wire mesh, a larger quantity of small droplets was observed compared to the no-mesh case. This was considered to be the result of droplets breaking upon colliding with the wires. However, in the case of the three-layered and six-layered mesh, the number of droplets decreased compared to the single-layer case. Especially in the six-layered case, very few small-diameter droplets were observed, while large droplets were observed. From these results, it was presumed that small droplets were captured in the layered wire mesh, and then large droplets were generated from the wire mesh due to re-entrainment.

Figure 6 shows the droplet diameter distribution represented by the mass frequency. The droplet diameter was evaluated by using the Oxford Lasers VisiSize Ver. 6 image processing system. Well-focused images of droplets, that is, images in which the boundary is clear, were selected for diameter evaluation. The interval of image acquisition was long enough to avoid capturing the same drops in multiple images. To obtain a smooth and accurate curve of droplet distribution, approximately 100,000 data items were acquired. The number of data items was examined by conducting pretests. However, in the cases of six-layered wire mesh of $d = 0.19$ and 0.8 mm, quite a long time was required for obtaining that many data items, so approximately 30,000 to 50,000 data items were obtained. Finally, valid images containing well-focused droplets totaled approximately 2,000 to 25,000 frames.

The mass frequency was calculated by the method described below. The mass of the i-th droplet is represented by the following formula:

$$m_i = \rho_L \frac{4}{3} \pi \left( \frac{d_i}{2} \right)^3$$  \hspace{1cm} (1)

where $\rho_L$ is the density of the droplet (kg/m$^3$) and $d_i$ is the diameter of the i-th droplet. Then, the summation of masses larger than 50 μm in diameter was calculated using the following equation:

$$M = \sum_{i=1}^{N} m_i = \sum_{i=1}^{N} \left[ \rho_L \frac{4}{3} \pi \left( \frac{d_i}{2} \right)^3 \right]$$  \hspace{1cm} (2)
Fig. 5 Example images of droplets at the downstream of the wire mesh, which were obtained by the CCD camera in the case of $d = 0.65$ mm for (a) no-mesh, (b) single-layer, (c) three-layered, and (d) six-layered configuration. In the single-layer case, a larger quantity of droplets was observed compared to the no-mesh case. In the six-layered case, very few small-diameter droplets were observed, while large droplets were observed.

The summation of masses in the range of

$$(1 - j)\Delta d < d \leq j\Delta d \quad j = 6, 7, 8, \ldots$$

is expressed as $\Delta m_j$. $\Delta d$ is the width of the histogram and here, $\Delta d = 10$ microns is used. The subscript “$j$” means the order of the histogram. In the present study, since the investigation range was droplets larger than $50 \, \mu m$ in diameter, which was the minimum measurable limit, $j = 6$ was the first histogram. For example, the mass frequency, $F$, between 50 and $60 \, \mu m$ was calculated as follows:

$$F = \frac{\Delta m_j}{M} \quad (3)$$

The mass frequency in each zone was calculated in the same manner.

The figures show the histogram for every 10 $\mu m$; however, lines were used instead of a bar chart. The vertical axis shows the mass frequency obtained as described above. In the no-mesh case, the droplet diameter was widely distributed up to 1300 $\mu m$. In the single-layer case of any wire diameter, a steeper peak at around 200 $\mu m$ was observed and droplets larger than 500 $\mu m$ decreased in comparison with the no-mesh case. This was caused by droplet breakage due to the inertia impact between the wire and the droplet.

The air involved in the fragmented droplets flowed toward the downstream through the layered wire mesh. In the case of three-layered mesh of $d = 0.19$ mm, the mass frequency of droplets larger than $500 \, \mu m$ increased. On the other hand, in the case of three-layered mesh of $d = 0.65$ and $0.80$ mm, the droplet diameter distribution was almost the same as each single layer. Considering that the wire mesh of $d = 0.19$ mm had an opening of 0.435 mm, which was much smaller than that of the other two types of wire mesh, it could be said that the diameter enlargement effect was stronger even in the three-layered wire mesh because of the high frequency of droplet capture in the wire mesh.

In the six-layered mesh, all wire diameter cases showed an increase in large droplets. Especially in the case of $d = 0.65$ mm, the outstanding feature of the microdroplet decrease was observed and the peak clearly shifted to about 700 $\mu m$. These results show that the number of mesh layers has a significant effect on droplet enlargement. Meanwhile, for the wire mesh of $d = 0.80$ mm, large droplets were observed but the microdroplets did not decrease. A remarkable droplet diameter peak shift to a large value did not appear for the six-layered configuration.
Fig. 6  Droplet diameter distribution for wire diameter of 0.19, 0.65 and 0.80 mm. Vertical axis shows the mass frequency of droplets. These figures show the histogram for every 10 μm and lines were used instead of a bar chart. In the single-layer mesh of all wire diameters, the mass frequency of droplets with a diameter of around 200 μm increased in comparison with that in the no-mesh case because of droplet breakage. In the case of six-layered mesh of \( d = 0.65 \) mm, the droplet diameter increased and a remarkable peak shift from 200 to 700 μm was observed.

3.2 Evaluation of moisture

We investigated the moisture, which is the mass fraction of the liquid phase in the bulk air–water two-phase flow using the locally measured droplet diameter data. In the layered wire mesh, after some of the droplets are captured, some are drained and the rest are carried over. If the mass flow of drained water could be measured precisely, the re-entrained mass flow of water could be obtained by taking the difference between the sprayed water mass flow and the re-entrained flow. Actually, because of droplets adhering to the wall of the flow passage and remaining on the wall, it was difficult to measure the mass flow of drained water. Hence, we estimated the mass fraction of the liquid phase in the bulk flow from the local mass fraction, which was obtained by the abovementioned measured diameter.

Firstly, the local droplet mass flow for the no-mesh case was calculated from the summation of the mass of each droplet using the measured diameter under the assumption that the droplet was a sphere. Then, the locally obtained total mass was divided by the sampling time. In the process, droplets with a diameter smaller than 50 microns were ignored. The local droplet mass flow is given by:

\[
G_{L1} = \frac{1}{(\Delta t)} \sum_{i=1}^{n} \left( \rho_{L} \cdot \frac{4}{3} \pi \left( \frac{d_{i}}{2} \right)^{3} \right)
\]

where the subscript “1” means “without wire mesh” and “x” means the local quantity. \( \Delta t \) is the sampling time. Using the same approach, the local droplet mass flow with wire mesh can be calculated as follows:
where the subscript “2” means “with wire mesh.” Then, the following relationship was assumed:

\[
\frac{G_{tL1}}{G_{L1}} = \frac{G_{tL2}}{G_{L2}}
\]  

(6)

where \(G_{tL1}\) represents the total mass flow of the liquid phase in an actual MSR without wire mesh, which was given from the design information. From Eq. (6), we predicted the total mass flow of the liquid phase in an actual MSR with wire mesh, \(G_{L2}\). After \(G_{L2}\) was obtained, the outlet droplet mass flow in an actual MSR with wire mesh, \(G_{L2,d≤D_{th}}\), was estimated by using the following equation:

\[
\frac{G_{tL2}}{G_{L2}} = \frac{G_{tL2,d≤D_{th}}}{G_{tL2,d>\bar{D}th}}
\]  

(7)

where the subscript “\(d≤D_{th}\)” means that only droplets smaller than \(D_{th}\) are considered. This is because droplets larger than \(D_{th}\) would be removed by the wave-shaped vanes installed at the downstream of the wire mesh. Then, we could obtain the moisture, \((1-x)_{d≤D_{th}}\) using the following relationship:

\[
(1-x)_{d≤D_{th}} = \frac{G_{tL2,d≤D_{th}}}{G_{tL2,d≤D_{th}} + G_{GL1}}
\]  

(8)

Figure 7 shows the relationship between the evaluated moisture and the number of layers of wire mesh. In the single-layer mesh of any wire diameter, the moisture increased compared with the no-mesh case. As mentioned above, this is the result of droplets colliding with the wire, breaking and entraining into the air. In the three-layered cases, the moisture was almost the same as in the no-mesh case. However, in the six-layered case of \(d = 0.65\) mm, it was confirmed that the moisture decreased significantly, from 0.45 to 0.08 wt%, compared with the no-mesh case. These results are consistent with the tendency in the droplet diameter distribution described above. Meanwhile, in both cases of \(d = 0.19\) and 0.80 mm, moisture reduction was not enhanced in the case of six-layered wire mesh. In the case of \(d = 0.19\) mm, the droplets were harder to hold in the wire mesh compared to the other two diameters since the total layered thickness of the wire mesh was small; thus, it was considered that the microdroplets were more easily carried over than the other two diameters. In the case of \(d = 0.80\) mm, the moisture increased. To clarify the reason for this, further investigation is required. However, the large thickness of the layered wire mesh and the wide opening might have affected the droplet enlargement process.

Fig. 7 Moisture evaluation results for wire diameter of 0.19, 0.65 and 0.80 mm. In the single-layer cases with any wire diameter, the moisture increased compared with the no-mesh case. The moisture decreased the most in the case of six-layered mesh of \(d = 0.65\) mm in all experimental cases, from 0.45 to 0.08 wt%, compared with the no-mesh case.
To consider the enlargement mechanism of the droplet size, we took photos near the wire mesh using a high-speed camera. Figure 8 shows an example of the visualization results obtained at the last layer of the six-layered wire mesh of \( d = 0.65 \) mm. From the photos, it was found that a liquid film had formed on the aperture of the wire mesh and the liquid film oscillated in the air flow direction. When the liquid film burst and detached from the wire mesh, liquid fragmented from the liquid film, generating enlarged droplets. It was considered that microdroplets from the upstream were captured in the layered wire mesh and liquid film formed on the aperture of the wire mesh by the liquid bridge effect, thus reducing the microdroplets. It was presumed that such a complex mechanism could result in droplet enlargement and microdroplet reduction.

![Diagram](image)

Fig. 8 Example of photos obtained by high-speed camera near the wire mesh on the downstream side. It was found that liquid film had formed on the aperture of the wire mesh. The liquid film burst and detached from the wire mesh and the fragmented liquid film became large-diameter droplets.

### 3.3 Characteristics of pressure loss

The pressure loss coefficient, \( \zeta \), was evaluated by the following approach:

\[
\frac{\Delta p}{\rho_G U^2} = \frac{\Delta p_{\text{No-mesh}}}{\rho_G U^2} - \zeta
\]

(9)

where \( \Delta p \) is the differential pressure between the upstream and the downstream of the wire mesh. The subscript “No-mesh” means “without wire mesh.” \( \rho_G \) is the gas-phase density and \( U \) is the mean velocity.

Figure 9 shows the relationship between the pressure loss coefficient and the number of wire mesh layers. The pressure loss coefficient increased with the number of layers for any wire diameter. In addition, the pressure loss coefficient decreased with the mesh diameter, which is a reasonable tendency since the aperture ratio of the wire mesh increases slightly with a bigger wire diameter, as shown in Table 3. The pressure loss coefficient of the single-layer mesh with diameter of 0.19 and 0.80 mm was 2.0 and 1.6, respectively, using the pressure loss coefficient correlation of wire mesh (Idelchik, 2008). The pressure loss coefficient of the single-layer mesh measured in our experiment was about 12–25 times the value by correlation. The reason why the measured values were much larger than those estimated by correlation was that the experimental flow condition was dispersed two-phase flow. According to Fig. 9, the moisture reduction rate was largest in the six-layered wire mesh of \( d = 0.65 \) mm; however, the pressure loss coefficient is largest in the six-layered wire mesh of \( d = 0.19 \) mm. It was found that the most effective wire mesh configuration for moisture reduction is not determined only by pressure loss. To clarify the droplet enlargement process, further investigation related to liquid bridge, liquid film formation and re-entrainment is required.
Fig. 9  Pressure loss measurement results with wire diameter of 0.19, 0.65 and 0.80 mm. The pressure loss coefficients increased with mesh layers for any wire diameter. The pressure loss coefficients decreased with the mesh diameter, which is a reasonable tendency since the aperture ratio of the wire mesh increased slightly with a bigger wire diameter.

4. Conclusions

In the present study, droplet diameter measurement, visualization by high-speed camera and pressure loss measurement were carried out for cases with different wire mesh diameter and number of layers. The results are summarized as follows.

a) In single-layer cases, the number of microdroplets increased compared with the no-mesh case. However, it was found that the mass frequency of large droplets increased with the number of layers. The droplet diameter increased the most in the case of six-layered wire mesh of $d = 0.65$ mm and the mass frequency peak shifted most remarkably from 200 to 700 $\mu$m.

b) In the case of six-layered wire mesh of $d = 0.65$ mm, the greatest moisture reduction effect was obtained, from 0.45 to 0.08 wt%. This result was consistent with the mass frequency of droplets.

c) From the photos taken by high-speed camera in the case of six-layered wire mesh of $d = 0.65$ mm, it was observed that the liquid film that formed on the aperture of the wire mesh oscillated in the flow direction and large droplets were generated by the eventual fragmentation of the liquid film.

d) The pressure loss coefficient of total wire mesh was largest in the case of six-layered mesh of $d = 0.19$ mm, not $d = 0.65$ mm, due to the small aperture ratio. It was found that the most effective wire mesh configuration for droplet enlargement is not determined only by pressure loss.

References


