Effect of Liquid Properties on Curtain Stability in Low Flow Rate

Hiroyasu FURUKAWA,1)* Hiroshi KANAI,2) Magonori NAGASE,3) Ryoji KOBAYASHI4) and Norbert ALLEBORN5)


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Curtain coating, which can achieve very high speed coating and smooth film without defects, is recently used to produce pre-painted steel sheets for home appliances and utensils. One of the difficulties limiting curtain coating operation arises from a low limit in flow rate, below which the falling liquid sheet breaks apart and we can not operate.

We measured the minimum flow rate for curtain formation for polyester resin solutions in very low Reynolds number (Re) experimentally, and found that the minimum flow rate decreased with decreasing surface tension and density, and with increasing viscosity of the liquids.

Relationship between the physical properties of the liquids and the minimum flow rate for curtain formation (curtain stability) was analyzed by using Reynolds number (Re) which represented the flow rate and Physical property number (Ka) which included surface tension, viscosity and density. As a result, the calculating formula by which the minimum flow rate can be estimated was given.

Further more, effects of surfactant on the minimum flow rate were studied. It is suggested that homogeneity of the surface is very important to stabilize the curtain, and if we use surfactants which decrease surface tension of the liquids uniformly, the curtain stability increases. In the range of this study, curtain stability is mainly dominated by liquid properties, and neither edge guides nor disturbances like bubbles in the liquids seem key factors for curtain stability.

KEY WORDS: curtain coating; liquid curtain stability in low flow rate; surface tension; density; viscosity; effect of surfactant.

1. Introduction

Roll coating has been mainly used to produce pre-painted steel sheets, however, recently a new production line for pre-painted steel sheets for home appliances and utensils has been built, in which curtain coating has been applied.1,2) Curtain coating has some advantages: firstly, it can coat at very high speeds, and secondly, it can coat very smooth film without defects named “ribbing” or “cascade” which often appear in roll coating. The first capability is attributed to the high impinging velocity of the liquid curtain sheet which is accelerated by gravity during falling down. The liquid pressure that results from the falling velocity can assist wetting of the substrate surface hydrodynamically, and can avoid air entrainment even in very high speed operations.3) The second capability arises from the long distance between the coating head and the moving substrate. Defects like ribbing in roll coating are derived from unstable pressure profile of the liquid going through very narrow gap of rolls or the roll and the substrate. They thought the second capability was especially very attractive to produce pre-painted steel sheets for home appliances and utensils which are required to have very smooth and uniform surface appearance without defects like ribbing.

One of the difficulties limiting curtain coating operation arises from a low limit in flow rate, below which the falling liquid sheet breaks apart and we can not operate. This means that when the substrate moving speed is constant, we can not decrease coated film thickness below a certain value which results from the low limit in flow rate and the substrate moving speed. We can obtain thinner film if we increase the substrate moving speed, however, in usual production lines of pre-painted steel sheets, steel coils are continuously painted, and we can not easily increase the moving speed of the sheet beyond the capacity of the facility. Then it is important for us to select kinds of liquid which has a lower limit in flow rate for curtain formation.

Greiller4) reported that the minimum flow rate to form a stable curtain with an aqueous gelatin solution is about 0.5 cm2/s in a slide hopper type curtain coater. He also demonstrated that if we added an appropriate surfactant to the

* Corresponding author: E-mail: furukawa.xd6.hiroyasu@jp.nssmc.com
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solution, it meant the surface tension of the solution decreased, the minimum flow rate to form a stable curtain decreased (the curtain became more stable), and there was a optimum viscosity range below and over which the curtain became more unstable.

Brown5) considered balance between surface tension force and inertial force at lower edges of a liquid sheet, and concluded that the inertial force $\rho u^2 d$ or $\rho Qu$ must be greater than the surface tension force $2\sigma$ for the liquid sheet formation. Here $\rho$ is the liquid density, $u$ is the curtain velocity at the impinging point, $d$ is the curtain thickness at the impinging point, $Q$ is the volumetric flow rate of the curtain per unit width, and $\sigma$ is the surface tension of the liquid. The resulting conditions for curtain stability is

$$\rho u^2 d > 2\sigma \quad \text{or} \quad \rho Qu / \sigma > 2$$

In dimensionless form, Eq. (1) becomes

$$We > 2$$

Where $We = \rho Qu / \sigma$ is Weber number which is the ratio of inertia force and surface tension force. Lin6) also obtained the same results from a theoretical linear stability analysis of falling liquid curtain. However, it has been pointed out that stable curtain often exist in conditions that violate the simple stability criterion of Eq. (2). The simple force balance, leading to the Weber number stability criterion, Eqs. (1) and (2), provides additionally an evolution equation for the rim forming at the curtain edge. The analysis of video image sequences of expanding holes in a falling liquid curtain of a fluid with low viscosity indicates good agreement between model and experiment.7,8)

Recent numerical results of Sunderhauf et al.9) indicated that viscosity may have a stabilizing influence on liquid curtains of finite length by slowing down the acceleration of a free edge in the curtain to its limit velocity predicted by the force balance mentioned above. These results show that although the simple balance does not take into account viscosity explicitly, it captures dissipation by a mechanism analogous to a plastic impact.

In this paper, we measured the minimum flow rate for curtain formation in very low Reynolds number ($Re$) experimentally, and tried to clarify effects of liquid viscosity, surface tension, and density on the low flow limit for curtain formation. We also tried to understand which force balances are important to form liquid curtain.

2. Experiments

2.1. Curtain Coater

In this study, the curtain coater on which the flow rate can be controlled by roll speed was used. The liquid film on the applicator roll was scratched together by a blade and free-fallen to form the curtain. The curtain width was 300 mm. The coater had an edge guide in both sides which was made by stainless steel ball chain (ball diameter: 5 mm). The length of the edge guide was 200 mm and a spherical leaden weight (diameter: 21 mm) was attached to the lower end of the edge guide to keep the incline vertical. The curtain height that is the distance from the curtain foot (the highest position) to the steel sheet position is usually 155 mm, however, in this study, it was 250 mm from the curtain foot to the position of liquid surface in the reservoir for collecting liquids. The liquid level in the reservoir was stable because the collected liquid in the reservoir was circularly reused.

2.2. Method of Minimum Flow Rate Measuring

The minimum mass flow rate for curtain formation was measured as follows: at first, the flow rate was increased to the flow rate at which curtain was formed without curtain break. Then flow rate was decreased gradually, and we judged minimum flow rate as the flow rate just before curtain breakage. A 100 mm wide rectangular container was inserted in the curtain for 60 s, and accumulated liquid in the container was weighted by electric mass scale, and we obtained mass flow rate per unit width and per unit time.

We observed where the curtain breakage occurred in curtain width direction at curtain height of 200 mm. The liquid falling down in the curtain was collected in the reservoir for recycling.

2.3. Liquids

Test liquids were polyester resin solutions without additives or surfactants. Three types of polyester resins were used in this study. Surface tension, viscosity, and density of the solutions were changed by changing kind and amount of solvents. Table 1 shows the polyester resins and Table 2 shows the solvents used in this study.

We prepared other polyester resin solutions to which we added surfactants to change the surface tension of the solutions. We used polyester resin A in this case. We used three kind of surfactants, acrylic deforming agents E and S, and silicon leveling agent M.

The ranges of physical properties of the liquids used in this study were as follows: surface tension $\sigma$ was varied from 26 to 41 mN/m, viscosity $\mu$ was varied from 0.3 to 2.9 Pa·s, and density $\rho$ was varied from 970 to 1 120 kg/m$^3$.

2.4. Methods of Liquids Properties Measurements

Viscosity of the liquids was measured by E type viscometer, Toyo Seiki Co.

Surface tension of the liquids was measured by Dynometer, Byko International.

Density of the liquids was measured by density float bottle. All the measurements were carried on in 20 degree C.
3. Results and Discussions

3.1. Curtain Breakage Behavior

We observed how and where curtain breakage occurred in the minimum flow rate for curtain formation and just below the flow rate. Figure 1 shows how curtain breaks. Figure 1(a) shows a stable curtain sheet in sufficient flow rate. In this flow rate, the curtain was stable enough, and even if we moved the container for measuring the flow rate in the curtain, the curtain did not break. With decreasing the flow rate, splits occurred at the lower edge of the curtain, however the splits did not extend to the upward of the curtain, and the curtain became stable again. When we decreased the flow rate further more, the splits extend to the upward of the curtain (Fig. 1(b)). When the splits reached to the foot of the curtain, the curtain broke and the liquid was falling down as droplets (Fig. 1(c)). At the minimum flow rate for curtain formation, we did not observe the splits, or we observed the splits in some cases once or twice a five minutes, and even if the splits occurred, the splits did not extend upward and disappeared soon. In just below the minimum flow rate, we observed the splits 2 or 3 times a minute, in some cases once a ten seconds, and the splits often went up the curtain to break the curtain. Curtain delamination (Fig. 1(d)) from the edge guides were rarely observed in this study. The split’s extension to the upward of the curtain was the main factor of the curtain breakage.

The position where the curtain broke in curtain width direction was random. Before the experiments, we expected that the edge guide area was the most probable position of the curtain breakage. However, the curtain breakage randomly occurred in the curtain width direction. The splits also occurred randomly.

We can often observe bubbles in the falling curtain sheet especially in high viscosity liquids. Bubbles in the curtain have been thought to be a factor of breakage of the curtain. However, in this study as mentioned later, the minimum flow rate for curtain formation decreased with increasing viscosity of the liquid. It is a seemingly strange result that liquids which have more bubble make more stable curtain. This means that, in the range of this study, edge effects and disturbance (bubbles) effects were not so strong factors for curtain stability.

3.2. Minimum Flow Rate for Curtain Formation for Liquids without Surfactants

Effects of viscosity and surface tension on minimum mass flow rate for curtain formation for polyester A solutions are shown in Fig. 2. The minimum flow rate decreased with decreasing surface tension and increasing viscosity of the liquids. This means curtain stability increased with decreasing surface tension and increasing viscosity. The minimum flow rate for curtain formation was ranged from 0.01 to 0.1 kg/(m s), and Reynolds number Re was ranged from 0.01 to 0.23. The minimum flow rate and the Re were relatively lower than those reported in the previous works. In the Greiller’s experiment, the Re was ranged from 1 to 30, and in the Brown’s experiment, the Re was ranged from 0.5 to 25. We can point out that this study was carried on in the very low Re which has not appeared in the previous works.

The relationship between the surface tension of the liquids and the minimum flow rate for curtain formation is shown in Fig. 3. Data around 0.9 Pa s were picked up from the Fig. 2 and were re-arranged in Fig. 3. The minimum flow rate decreased apparently with decreasing surface tension of the liquids. When we used solutions of polyester B and C, similar tendency was observed as Fig. 2.

As breaking force of the curtain is mainly thought to be surface tension, it is understandable that the curtain becomes more stable with decreasing surface tension of liquids. Also, as viscosity is thought to be a resisting force for breakage of curtain, it is reasonable that curtain becomes more stable with increasing viscosity of liquids. However, Greiller’s results showed that there was optimum viscosity below and over which the curtain became more unstable, and his results were different from those in this study, Miyamoto suggested that increasing viscosity accelerated the development of unstable boundary layer along the edge guide and promoted the curtain breakage, and then there was the opti-
mum in viscosity.\textsuperscript{11,12} We thought that because edge effects were not key factors for curtain stability in the range of this study and the edge area did not affect the curtain breakage, the curtain could exist stable even when the liquid had high viscosity.

We tried to understand the effects of the liquid properties on the minimum flow rate for curtain formation further and tried to express the results in dimensionless form. Relationship between the physical properties of the liquids and the minimum flow rate for curtain formation (curtain stability) was analyzed using Re which represented the flow rate and physical property number (Ka) which included surface tension, viscosity and density. Here, Re and Ka were expressed as follows respectively,

\begin{equation}
Re = \frac{\rho ud}{\mu} \quad \ldots (3)
\end{equation}

\begin{equation}
Ka = \frac{\sigma^3 \rho}{g \mu^4} \quad \ldots (4)
\end{equation}

\(\sigma\): surface tension of liquid, \(g\): gravity acceleration

**Figure 4** shows the relationship between the Re and the Ka at the minimum flow rate for curtain formation for all the liquids without surfactants. The Re and the Ka had linear relationship and we obtained Eq. (5) at the minimum flow rate for curtain formation from the Fig. 4.

\begin{equation}
Re = K_1 Ka^n = K_1 \left(\frac{\sigma^3 \rho}{g \mu^4}\right)^n \quad (K_1=0.29, \ n=0.34) \ldots (5)
\end{equation}

From Eq. (5), we can obtain Eq. (6).

\begin{equation}
Q = \rho ud = 0.134 \cdot \sigma^{1.0} \cdot \rho^{0.34} \cdot \mu^{-0.35} \ldots (6)
\end{equation}

\(Q\) is the minimum mass flow rate for curtain formation. \(Q\) decreases with decreasing surface tension and density, and with increasing viscosity. It is understandable that surface tension has largest impact in the liquid properties to the minimum flow rate for curtain formation because the ratio of surface area to the volume of the liquid is large in low flow rate region as this experiment.

**Figure 5** shows the relationship between the calculated minimum flow rate \(Q_{\text{calcd}}\) using Eq. (6) and the measured minimum flow rate \(Q_{\text{measd}}\). As shown in Fig. 5, a good correlation between \(Q_{\text{calcd}}\) and \(Q_{\text{measd}}\) is seen. It is thought that we can estimate the minimum flow rate for curtain formation by Eq. (6).

\(Ka\) can also be described as the followings;

\begin{equation}
Ka = \frac{\sigma^3 \rho}{g \mu^4} = \left(\frac{\sigma}{d}\right)^2 \left(\frac{\sigma}{\rho gd}\right) \left(\frac{\rho u^2}{\mu u/d}\right)^2 
\end{equation}

\begin{equation}
= \left(\frac{\text{surface tension force/viscous force}}{\text{gravitational force}}\right)^2 \left(\frac{\text{inertia force/viscous force}}{\text{gravitational force}}\right)^2 \ldots (7)
\end{equation}

From Eqs. (5) and (7), we can obtain Eq. (8).

\begin{equation}
Re = K_2 \left(\frac{\sigma}{d}\right)^2 \left(\frac{\sigma}{\rho gd}\right)^{1.1} \left(\frac{\rho u^2}{\mu u/d}\right)^{2.1} \quad (K_2=1.7 \cdot 10^{-3}) \ldots (8)
\end{equation}

As Re represents flow rate (in this case, the minimum flow rate for curtain formation), this relationship means the low flow limits for curtain formation is dominated by both force balances between surface tension force and viscous force, and surface tension force and gravitational force, the first and the second term in Eq. (8), respectively. And the minimum flow rate decreases (curtain becomes more stable) with decreasing the respective ratios.

### 3.3. Effects of Surfactants on Minimum Flow Rate for Curtain Formation

**Figure 6** shows effects of 0.5% surfactants addition on
the minimum flow rate for curtain formation. Polyester A solutions in cyclohexanone/Solvesso 150, 0.9 Pa s in viscosity, and 32 mN/m in surface tension were used. Before the experiments, we supposed that the surfactants decrease the surface tension of the liquids to increase the curtain stability. However, all surfactants decreased the surface tension of the liquids, however only the surfactant M decreased the minimum flow rate and increased the curtain stability. Surfactants E and S decreased the surface tension, but also decreased the curtain stability. We measured surface tension of the liquids to clarify the reason. Figure 7 shows surface tension of the liquids with and without surfactants. The surface tension of each liquid was measured five times. Apparently, when the surfactant E or S was added, the variation of the measured values was wider compared with when the surfactant M was added or no surfactant was used. Solid lines indicate the surface tension of the surfactants themselves. In the case of the surfactant M, the liquid surface tension was as same as that of the surfactant itself, while in case of the surfactants E and S, the liquids surface tension were higher than that of the surfactants themselves. This means that the surfactant M was perfectly or uniformly absorbed on the surface of the liquid, while the surfactants E and S were un-uniformly absorbed on the surface. We thought that surfactant M was designed for leveling agent which was required to absorb liquid surface uniformly so that the surface tension of the liquid decreased uniformly, while surfactants E and S were designed for anti-foaming agents which were required to absorb the surface of the liquid un-uniformly so that the surface tension differences caused to rupture bubbles or foams. Compared E with S, S increased the minimum flow rate more than E. Judging from Fig. 7, the surface tension variation of S is larger than that of E. This means S make the surface more un-uniform to disturb curtain stability more than E. These results suggest that surfactants which decrease the surface tension and keep the surface homogeneity, increase curtain stability, while surfactants which disturb surface homogeneity even if they decrease the surface tension, tend to decrease the curtain stability.

3.4. Effect of Edge Guide on Curtain Stability

In industrial heat exchange facilities, heat in fluid going through in the pipes can transfer to the liquid falling down the pipes. By Mitrovic,13) falling behavior of the liquid were classified in the three forms, droplets, jets, and a sheet shown in Fig. 8. There are some reports which studied effects of the flow rate of the falling liquid, the liquid properties and the special configuration of the pipes on the falling behavior of the liquid. Armbruster et al. indicated that the critical flow rate for liquid sheet formation was shown in Eq. (9), which is very similar to Eq. (5).

$$Re = A \cdot Ka^n = 0.57 Ka^{0.25}$$  \hspace{1cm} (9)

They said the constants A depended on kind of liquids, and n depended on the special configuration of pipes. We can notice that although liquid curtain is formed without edge guide in the facility of Fig. 8, the critical flow rate for liquid sheet formation can express the very similar form shown in this study. This fact suggests that boundary layer near edge guide which is often considered as one of causes for breakage of curtain does not so strongly affect the stability of the curtain in this study. Randomness of the curtain breakage position in width direction also suggests this notion. It is concluded that liquid properties dominates curtain stability in the range of this study.
4. Conclusions

We measured the minimum flow rate for curtain formation for polyester resin solutions in very low Reynolds number (Re) experimentally, and found that the minimum flow rate decreased with decreasing surface tension and density, and with increasing viscosity of the liquids. Furthermore, effects of surfactant on the minimum flow rate were studied. It is suggested that homogeneity of the surface is very important to stabilize the curtain, and if we use surfactants which decrease surface tension of the liquids uniformly, the curtain stability increases. In the range of this study, curtain stability is mainly dominated by liquid properties, and neither edge guides nor disturbances like bubbles in the liquids seem key factors for curtain stability.

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REFERENCES