A Study on Intermittent Water Jet
Effects of Pump Pressure, Supplementary Air Flow and Water Surface Tension

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Abstract

Several methods were devised to study the behavior of the intermittent water jet used in the water jet loom, and the effects of the pump pressure, the supplementary air flow along the jet-stream and the water surface tension on the transition of the jet flow pattern, the jet-head velocity and the break-up length are observed, where the break-up length is the distance from the nozzle to a point where the jet-stream first breaks its continuity. The followings are the main results obtained:

1. As the jet goes further from the nozzle, its flow pattern changes continuously from the smooth flow to the wavy flow and finally becomes the spray flow. There is a fist-like bump at the jet-head in the wavy flow.
2. The higher the pump pressure, the faster the transition of the flow pattern and the faster the highest jet-head velocity, but the shorter the break-up length.
3. The supplementary air flow retards the transition of the flow pattern and increases the break-up length.
4. The lower the water surface tension, the longer the break-up length. But some surface active agents increase the water viscosity and lower the highest jet-head velocity.

1. Introduction

This paper concerns with an intermittently gushed out water jet used for inserting wefts in a water jet loom, i.e., a small amount of water is spouted from an annular nozzle with a weft in its inner tube. It is necessary to increase the jet velocity for increasing the weft velocity. This hastens, however, the dispersion or atomization of the jet and gives the weft undesirable effects such as bending or folding on its insertion. Thus, the jet is desired to be atomized as late as possible even at high velocity.

However, as the behavior of the jet with the weft is too complicated to be analysed, only the behaviors of the jet with no weft are investigated here. The jet flow pattern, jet-head velocities and the break-up length and how these quantities are effected by the relative velocity between the jet-head and the air around it are studied. The break-up length here used is the distance from the nozzle to the position where the jet breaks first its continuity, and is regarded as a measure of the degree of the atomization, i.e., the longer the break-up length is, the later the atomization occurs. The water surface tension is also studied, because this is a measure of the easiness to atomization, i.e., the higher the water surface tension, the easier the water becomes small droplets. The relative velocity is changed by changing the pump pressure and/or by adding supplementary air flow along the jet-stream. The water surface tension is adjusted by adding surface active agent in the water.

2. Experimental

2.1 Injection Pump and Injection Nozzle

The cross sectional drawing of the injection pump employed is shown in Fig. 1, in which plunger 7 in cylinder 5 is pulled up by injection cam 2 rotating clockwise and then pushed down by the force of spring 6. Thus, water is charged into the cylinder from a reservoir through pipe 4 and then discharged into a injection nozzle through pipe 3.

The water from the injection pump flows into the annular tube of the injection nozzle shown in Fig. 2 through pipe 1 and holes 2, and then injected into the atmosphere from outlet 4. Inner tube 3 is a thread guide for weft inserting, the
inlet of which is, however, closed and no weft is inserted in this experiment. The nozzle is set vertical to inject water straight downward for preventing its stream from curving by gravity.

2.2 Timing Apparatus

The timing apparatus shown in Fig. 3 and used to synchronize the camera with a jet stream consists of three steel discs 5, 6, and 7 set on cam shaft 2. Disc 6 is fixed to bearing stand 4, and does not rotate. Disc 7 rotates with cam shaft 2, and has a piece of insulator 8 made of phenol resin on its circumference. Disc 5 can be turned around on the boss of disc 6 when thread 3 is loosened. A radial stem 10 made of phenol resin is set on disc 5, and at its end has copper terminals 9 which contact with the circumference of disc 7. Thus, the circuit is made except when the terminals contact with the insulator. Hereafter, the angle between the positions when the vertex of the injection cam is vertical and when the insulator is vertical is called lag angle. The lag angle $\theta$ [deg.] can be adjusted by rotating disc 5, and corresponds to the time $\theta/60N$ passed after the beginning of the injection, where $N$ is the cam rotational speed [rpm].

2.3 Streak Camera

A streak camera shown schematically in Fig. 4 is made to take photographs of a jet-stream continuously; light reflected from the jet is focussed on a sheet of film wound round the circumference of drum 6 (100 mm$^{2}$) through lens 1, shutter 2 and slit 4. Drum 6 is driven at a constant speed by motor 8, the revolution of which can be adjusted so that drum 6 may rotate exact only one cycle during the opening of shutter 2. The visual field is viewed through finder 9 after reflected by mirror 3.

2.4 Method for Measuring Break-Up Length

Photographs of jets are taken by a stroboscope, the flashing timing of which is adjusted by the lag angle. The position where the first break-up of the jet occurs is read out from these pictures with a scale photographed simultaneously with the jet stream.

Fig. 5 shows three examples of them, in which white horizontal short lines indicate the position of the break-up and the numbers in white regions represent the distance [cm] from the nozzle. These examples show that the positions of break-up are not fixed even under the same conditions and are very ambiguous. Thus, as the experimental error of the break-up length can not be neglected, we use $t$-test to find the significant difference among average break-up lengths.

2.5 Method for Measuring Jet-Head Velocity

A system for measuring the jet-head velocity is shown schematically in Fig. 6: The shutter of streak camera 1 is connected mechanically with movable core 4 of electromagnet 5 connected electrically with the terminals of timing apparatus 6 through A.C. 100 volt source. When the termi-
nals contact with the insulator in the timing apparatus, the shutter is released by the force of spring 3, i.e., simultaneously with the beginning of the water injection when the lag angle is zero. Furthermore, the streak camera 1 takes a streak of jet 11 illuminated by lamp 12 as well as timing marks on the same frame made by stroboscopic light 7 (25,000 rpm) through pin hole 8. The camera also takes a picture of scale 9 on the same frame.

One of such pictures is shown in Fig. 7, in which the white curved line 1 from the left top to the right bottom is the streak of a jet-head. A white dot 2 is one of timing marks from which the jet-head velocity can be measured.

2.6 Experimental Condition

Table 1 shows experimental conditions employed, where $P_0$ is the initial pump pressure, $V_a$ the initial velocity of the supplementary air flow, $\sigma_w$ the water surface tension. $P_0$ is given by $P_0 = 4kl/\pi d^2$, where $k$ is the spring constant of spring 6 in Fig. 1, $d$ the diameter of cylinder 7, $l$ the total compression of spring 6.

Fig. 8 shows the configuration of a pair of auxiliary nozzles employed for supplementary air flow. The nozzles are made of circular pipes with inner diameter 16 [mm], and 36 [mm] distant from each other at their outlets, arranged symmetrically to the axis of the main nozzle. Axes of auxiliary nozzles intersect at an angle of 6.5 degree. The initial velocity $V_a$ in Table 1 means the axial air-flow velocity from each auxiliary nozzle measured at its outlet. Fig. 8 shows also the resultant velocity-distribution of the supplementary air flow measured by a pitot-static tube along the axis of the main nozzle.

Surface active agent (nonil-phenol) was used for reducing the water surface tension which was measured by a capillary tube method[11].

3. Results and Discussion

3.1 Transition of Flow Pattern

It was observed that the jet changes its flow pattern continuously as it goes further from the nozzle. The jet near the nozzle (about 1 cm) is continuous, laminar and transparent, and we call it "smooth flow". Then, it changes to continuous, but opaque white flow with wavy surface. This wavy flow continues to the first break-up point (about 30 cm). Repeating the break-up, after this point, the jet becomes discrete flow with many droplets, resulting in spray flow.

Followings were also observed: i) transition of a jet mentioned above is accelerated by raising the initial pump pressure $P_0$, while retarded by the supplementary air flow and

![Fig. 6 System for measuring jet-head velocity](image)

![Fig. 7 Streak of jet-stream (part)](image)

![Fig. 8 Velocity distribution of supplementary air flow](image)

<table>
<thead>
<tr>
<th>Table 1 Experimental conditions</th>
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<td>Experimental condition</td>
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<tr>
<td>$P_0$ (kg/cm$^2$)</td>
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<tr>
<td>$V_a$ (m/s)</td>
</tr>
<tr>
<td>$\sigma_w$ (dyn/cm)</td>
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by reducing the water surface tension, ii) there exists a fist-like bump at the jet-head in the domain of the wavy flow. The bump is considered to occur because the jet-head is overcome and pushed by the rear faster jet and is spreaded out. The existence of such velocity difference can be understood both by the jet-head velocity measurement mentioned later, and by the following reasons: (1) the water in the pump is accelerated from a standstill. (2) the jet-head suffers heavier air resistance than the following part.

Fig. 9 shows examples of jet flows in which (a) represents the transition from smooth to wavy flow (between 0 and 10 cm), (b) wavy flow (to about 30 cm) and (c) the transition from wavy to spray flow (between 40 and 70 cm).

3.2 Jet-Head Velocity
Figures 10 to 12 show jet-head velocity distributions under experimental conditions in Table 1. Each point indicates the average of five measurements. It is clear from these figures that the jet-head is accelerated after it leaves the nozzle, reaching the highest velocity at a distance about 15-25 cm from the nozzle, and then is slowed down linearly. As the jet-head cannot become faster by itself after leaving the nozzle, it is easy to see that such seeming acceleration is due to being pushed, or in other words being usurped by the rear faster part as described previously. Furthermore, comparing these results with Fig. 13, we can find that the distance reaching the highest velocity is very close to the break-up length. This fact suggests that the jet-head after reaching the highest velocity has no rear part faster than that, and becomes slower by air resistance and atomization.

Fig. 10 shows the effect of the initial pump pressure $P_0$ on the jet-head velocity in the case of no supplementary air flow and no surface active agent. It is clear that the stronger the initial pump pressure, the higher is the highest velocity when $P_0$ is between 10 and 16 [kg/cm²].

Fig. 11 shows the effect of the supplementary air flow on the jet-head velocity in the case of $P_0 = 16.3$ [kg/cm²] and no surface active agent. It is clear that the supplementary air flow makes the decrease of the jet-head velocity less, but gives little effect on increasing the highest velocity although the configuration of a pair of auxiliary nozzles was thought most preferable after many preliminary experiments. Fig. 8 shows that the supplementary air flow reaches its highest velocity near the point where the jet-head reaches its highest velocity. These facts suggest that the supplementary air flow has such effect as making the decrease of the jet-head velocity less mainly because the jet atomization is slowed down rather than the air resistance is reduced. This is also confirmed by the change of the break-up length shown in Fig. 13.

Fig. 12 shows the effect of the water surface tension $\sigma_w$ on the jet-head velocity when $P_0 = 16.3$ [kg/cm²] and $V_a = 0$. It is clear that the surface active agent lowers and retards the highest jet-head velocity. Furthermore, it relaxes the deceleration of the jet-head velocity after reaching its highest velocity. So, the jet-head velocity can be made higher after the jet reaches about 40 cm if the surface active agent is used. The slow deceleration may be due to the lower water surface
tension by which the jet atomization is retarded. It should be noted that the non-ionic surface active agent such as nonil-phenol employed here is liable to increase the water viscosity, thus the fall of the highest jet-head velocity may be due to the increase of the friction loss of the nozzle, pipes and the pump.

3.3 Break-Up Length

Fig. 13 shows the break-up length, in which each point indicates the average of 150 measurements and the short vertical line the standard deviation in measured values. The number attached to the point corresponds to the experimental condition shown in Table 1. Table 2 shows the results of t-test at significance level $a = 2.5\%$. The initial pump pressure, the supplementary air flow and the water surface tension give significant effect on the break-up length, i.e., higher $P_0$ reduces the break-up length, and higher $V_a$ or lower $\sigma_w$ increases the break-up length.

4. Additional Notes

This is the first step for investigating the intermittent water jet used in the water jet loom. Following notes may be informative to future investigation:

1. It was found that the open thread guide with no weft gushes out the jet somewhat different in flow patterns from those of the closed thread guide employed here. This fact suggests the existence of air flow from the open thread guide into the jet-stream.

2. It is reported that some ethylene-oxide agent reduces water flow turbulence, and hence increases the flow-rate in hoses used in fire-fighting. So, various surface active agents should be examined to find the most appropriate one to the water jet loom.

3. Photographs for measuring the break-up length should be taken in different directions, since the jet may appear continuous even if it is broken up when observed only in one direction.

4. Alternative method for measuring the jet-head velocity in the range of spray flow should be considered, since the light reflected from the jet is too weak to take a photo.

5. Conclusion

Several methods were devised to study the behavior of the intermittent water jet, and the effects of the initial pump pressure, the supplementary air flow along the jet-stream and the water surface tension on the transition of the jet flow pattern, the jet-head velocity and the break-up length were observed. The followings are the main results obtained.

1. As the jet goes further from the nozzle, its flow pattern changes continuously from the smooth flow near the nozzle outlet, to the wavy flow and finally becomes the spray flow. There is a fist-like bump at the jet-head in the wavy domain.

<table>
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<td>$b_i = b_f$?*</td>
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<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

* $b_i$ is the average of the break-up length for condition $i$.

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(2) The higher the initial pump pressure, the faster the transition of the flow pattern and the faster the highest jet-head velocity, but the shorter the break-up length.

(3) The supplementary air flow retards the transition of the flow pattern and increases the break-up length.

(4) The lower the water surface tension, the longer the break-up length. But some surface active agents increase the water viscosity and lower the highest jet-head velocity.

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References