Analysis of Yarn Tension in Air-jet Nozzles

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Abstract

In the insertion of yarns by air-jet, the yarn acceleration in the jet nozzle is one of the important factors. The present investigation is planned to discuss the yarn tension mechanism in nozzles as follows.

- 1) Air flow rate and its velocity in nozzles are measured experimentally.
- 2) The drag force acting on different kinds of yarns according to yarn structure and count is measured. The yarn tension obtained is compared with the theoretical value calculated from the drag coefficient based on the Reynolds number.

The results obtained were as follows.

- 1) An increase of the bore size of the induction nozzle provided in the jet nozzle increases the air flow rate induced by driving flow. The maximum bore size was 3 mm.
- 2) The induced flow rate reached a limited value in spite of increasing the driving pressure.
- 3) The applied tension on the yarn in a jet reached a limited value in spite of increasing the length of the acceleration pipe.
- 4) The yarn tension calculated from equations based on the isentropic flow of compressible fluid and the air drag in the nozzle were in agreement with those obtained experimentally.

1. Introduction

Jet looms that use fluid for filling insertion have been introduced to take the place of traditional shuttle looms in recent years, and increased their productivity more than three times. There are both air-jet looms using air and water-jet looms using water for filling insertion. In this paper, the air-jet is only investigated.

Uno et al.^[1] studied the yarn propulsion into free atmosphere as a basic investigation on air-jet looms. Recently Mohamed et al.^[2] studied the relation between the nozzle design and its performance for filling insertion. However the relation between air flow in the jet nozzle and yarn tension applied on it have not been ascertained. Therefore the following two points were investigated in this experiment.

- 1) Air flow rate and its velocity in nozzles are measured experimentally. Driving pressure, the bore size of the induction nozzle and several conditions in the nozzle body are selected as test parameters.
- 2) The drag force acting on different kinds of yarns according to yarn structure and count is measured. The yarn tension obtained is compared with the theoretical value calculated from the drag coefficient.

2. Experiment

2.1 Air-jet nozzle

The air-jet nozzle used in this experiment is shown schematically in Fig. 1. This nozzle mainly consists of induction nozzle (a), nozzle body (b) and acceleration

Fig. 1 Schematic diagram of nozzle

tube (c). The induction nozzle is 35 mm in length and 6 mm in outer diameter, and its inner diameter D_2 is varied as one of the experimental parameters. The nozzle body has 32 mm in outer diameter and 5 mm in bore diameter. The acceleration tube has 5 mm in inner diameter, and its length L_a is varied as another one of the experimental parameters. X axis is in the axial direction of the induction nozzle. Induction nozzle (a) has 0.5 mm pitch male thread and is threaded into nozzle body (b). Full clockwise threaded position of (a) (the broken line in Fig. 1) is taken to be $X=0$. The position of the induction nozzle tip at $X=0$ is placed 9 mm away from the left end of the nozzle body. The cross sectional area of driving flow f_1 varies with changes in the position of X resulting in the change of driving flow rate Q_1 .

The air pressure at the exit of induction nozzle (a), is lower than atmospheric pressure by driving flow f_1 ,

and induced flow f_2 is generated from the entrance of the induction nozzle to the mixing area. Induced flow f_2 at the exit of the induction nozzle is driven into the acceleration tube by the viscosity of f_1 . f_1 and f_2 are mixed almost completely in bores of body ③ and acceleration tube ④, and jetted into the atmosphere as mixed flow f_3 . The yarn behind the induction nozzle is drawn into the nozzle by flow f_2 , and is accelerated and released into the air by flows f_2 and f_3 .

2.2 Air flow in the nozzle

The apparatus to measure the air flow in the nozzle is shown schematically in Fig. 2. Compressor ① supplies

Fig. 2 Schematic diagram of measurement of flow in the nozzle

nozzle body ③ with driving flow f_1 at a constant pressure through pressure regulator valve ②. Air pressure of the driving flow is measured by a gauge in the regulator valve. In order to measure mixed flow rate Q_3 , the air velocity at the exit of acrylic pipe ⑤, V_E , is measured by an anemometer and a hot wire probe ⑥. This pipe has an honeycomb whose coefficient of discharge is 0.95. Q_3 is calculated with the equation of continuity.

$$\rho_3 \cdot Q_3 = \rho_3 \cdot V_3 \cdot A_3 = \rho_E \cdot V_E \cdot A_E = \text{const.} \dots (1)$$

where ρ is the air density, V is the air velocity, A is the cross sectional area. The subscript "3" indicates the values relating to mixed flow f_3 , and the subscript "E" indicates the values relating to exit of ⑤. ρ_E can be regarded as atmospheric density ρ_0 because the velocity at the exit of ⑤ is not more than 4.8 m/sec. Q_3 , therefore, is obtained by

$$Q_3 = A_3 \cdot V_E / 0.95 \dots (2)$$

where A_3 is the cross-sectional area of acceleration tube ④ and V_E is measured from ⑥.

These measurements were performed for testing conditions shown in Table 1. The driving pressure, for example, varies from 0.5 atg to 4.0 atg with an increment of 0.5 atg. Q_1 is obtained as Q_3 at $Q_2=0$ using the $D_2=0$ induction nozzle. On the other hand, Q_2 is obtained from the difference between Q_3 and Q_1 .

Table 1 Test parameters of flow in the nozzle

PARAMETERS	KINDS	LOWER LIMIT	UPPER LIMIT	PITCH
p_v (atg)	8	0.5	4.0	0.5
D_2 (mm)	4	1.5	3.0	0.5
X (mm)	6	0.0	2.5	0.5
L (mm)	12	0.0	110.0	10.0

p_v : DRIVING PRESSURE
 D_2 : BORE OF INDUCTION NOZZLE
 X : AMOUNT OF RETREATMENT OF INDUCTION NOZZLE
 L : LENGTH OF ACCELERATION TUBE

2.3 Effect of length of the acceleration tube

The apparatus to measure the yarn tension induced in the nozzle is shown schematically in Fig. 3. The

Fig. 3 Schematic diagram to measure the yarn tension in the nozzle

induced yarn tensions are measured in several acceleration tubes of different length L_a in order to investigate the effect of L_a on the yarn tension. L_a varies from 0 up to 130 mm in increment of 10 mm. Compressor ① supplies a constant pressure through pressure regulator valve ② and the yarn is drawn into the nozzle. The yarn tail is attached to U gauge ⑤. The signals obtained from ⑤ is output by recorder ⑦ through the amplifier ⑥. The yarn tension is measured as F_0 when the yarn tip is at the exit of the acceleration pipe, and the tension is to be F_{200} when the yarn is extended 200 mm from its exit. Yarn tension induced in the jet during 200 mm from the exit of the nozzle are obtain as $F_{\text{jet}} = (F_{200} - F_0)$. In this experiment, the testing conditions are at the driving pressure $p_v = 1.0$ atg, the inner diameter of the induction nozzle $D_2 = 3.0$ mm and its position $X = 1.0$ mm. Nylon monofilament yarn 16.8 tex is used for its specimen.

2.4 Yarn tension in the nozzle

Yarn tension of different kinds of fibers induced in the nozzle is measured by means of the arrangement shown in Fig. 3. The different kinds of yarn specimens in their structure and projected diameter are shown in Table 2. Test conditions are at the driving pressure $p_v = 1.0$ atg, the inner diameter of the induction nozzle

Table 2 Yarn diameter

SPECIMEN	tex	d (mm)
NYLON MONOFILAMENT	16.8	0.133
	28.2	0.185
COTTON	7.4	0.144
	9.8	0.138
	19.7	0.239
POLYESTER MULTIFILAMENT	27.8	0.249

d : PROJECTED DIAMETER

$D_2 = 3.0$ mm, its position $X = 1.0$ mm and the length of the acceleration tube $L_a = 50$ mm. The method of measurement is the same as that mention in the previous section.

3. Theory

3.1 Air flow in the nozzle

Now consider the air flow in the nozzle based on the isentropic flow^[3] (reversible and adiabatic flow). Bernoulli's equation can express the relation between the atmospheric state 0 (air density ρ_0 , air pressure p_0 , air velocity V_0) and the state 2 (air density ρ_2 , air pressure p_2 , air velocity V_2) at the exit of the induction nozzle:

$$\frac{\kappa}{\kappa-1} \cdot \left(\frac{p_2}{\rho_2} - \frac{p_0}{\rho_0} \right) + \frac{V_2^2 - V_0^2}{2} = 0 \dots \dots (3)$$

where κ is the ratio of specific heats. V_0 equals zero at the atmospheric state. Though the friction loss is not considered in eq. (3), it should not be ignored in the case of the nozzle where high speed air flow runs in the narrow path. Therefore we introduce a coefficient α_2 as follows

$$\alpha_2 \cdot \frac{V_2^2}{2 \cdot g} = \frac{V_2^2}{2 \cdot g} + \xi_2 \cdot \frac{V_2^2}{2 \cdot g} + \lambda_2 \cdot \frac{L_2}{D_2} \cdot \frac{V_2^2}{2 \cdot g}$$

$$= (1 + \xi_2 + \lambda_2 \cdot \frac{L_2}{D_2}) \cdot \frac{V_2^2}{2 \cdot g} \dots \dots (4)$$

where g is the acceleration of gravity, ξ_2 is the loss coefficient at the entrance of the induction nozzle, λ_2 is the friction factor in the induction nozzle, L_2 is its length and D_2 is its bore. Eq. (3), therefore, changes as follows.

$$\frac{\kappa}{\kappa-1} \cdot \left(\frac{p_2}{\rho_2} - \frac{p_0}{\rho_0} \right) + \alpha_2 \cdot \frac{V_2^2}{2} = 0 \dots \dots (5)$$

In the same manner as above, for the relation between the state 2 at the exit of the induction nozzle and the state 3 (air density ρ_3 , air pressure p_3 , air velocity V_3).

$$\frac{\kappa}{\kappa-1} \cdot \left(\frac{p_3}{\rho_3} - \frac{p_2}{\rho_2} \right) + \frac{1}{2} \cdot (\alpha_3 \cdot V_3^2 - V_2^2) = 0$$

$$\dots \dots \dots (6)$$

where

$$\alpha_3 = 1 + \xi_3 + \lambda_3 \cdot (L_3/D_3) \dots \dots \dots (7)$$

where ξ_3 is the combining loss coefficient of f_1 and f_2 , λ_3 is the friction factor in the acceleration tube, D_3 is its bore and $L_3 = L_a + X + 9$ mm (see Fig. 1).

For the adiabatic change, on the other hand, the following equation is formed between the air pressure p and its density ρ .

$$p/p_0 = (\rho/\rho_0)^\kappa \dots \dots \dots (8)$$

Substituting eq. (8) into eq. (5) and eq. (6) respectively, we have

$$\frac{\kappa}{\kappa-1} \cdot \frac{p_0}{\rho_0} \cdot \left\{ \left(\frac{Q_{E2}}{V_2 \cdot A_2} \right)^{\kappa-1} - 1 \right\}$$

$$+ \alpha_2 \cdot \frac{V_2^2}{2} = 0 \dots \dots \dots (9)$$

$$\frac{\kappa}{\kappa-1} \cdot \frac{p_0}{\rho_0} \cdot \left\{ \left(\frac{Q_{E3}}{V_3 \cdot A_3} \right)^{\kappa-1} - \left(\frac{Q_{E2}}{V_2 \cdot A_2} \right)^{\kappa-1} \right\}$$

$$+ \frac{1}{2} \cdot (\alpha_3 \cdot V_3^2 - V_2^2) = 0 \dots \dots \dots (10)$$

where Q_{E2} and Q_{E3} are converted flow rate of Q_2 and Q_3 into the atmospheric state respectively.

Using eq. (9) and eq. (10), V_2 and V_3 can be calculated numerically from the measured value of Q_E . Table 3

Table 3 Coefficient of loss in nozzle

POSITION	D_2 (mm)	H	ξ_2	ξ_3	$\lambda \cdot \frac{L}{D}$	α
IN INDUCTION NOZZLE	1.5	1	0.50		1.35	2.85
	3.0	1	0.25		0.53	1.78
IN ACCELERATED TUBE	1.5	1		-1.80	0.44	-0.36
	3.0	1		0.05	0.44	1.49

D_2 : BORE OF INDUCTION NOZZLE

H : COEFFICIENT OF VELOCITY HEAD

ξ_2 : LOSS COEFFICIENT OF ENTRANCE

ξ_3 : LOSS COEFFICIENT OF COMBINING

$\lambda \cdot \frac{L}{D}$: LOSS COEFFICIENT OF PIPE FRICTION

α : $H + \xi_2$ (OR ξ_3) + $\lambda \cdot \frac{L}{D}$

shows the coefficient of loss in each portion of the nozzle that is used for numerical calculation. The friction factor in this table is obtained from Moody diagram^[4] on the assumption of the turbulent flow condition. The combining loss coefficient is taken from the loss in combining junction^{[5]-[7]}. Data for the case of water is used as these coefficients of loss. Examples of the case in which the driving pressure p_v is 1.0 atg, the amount of retreatment of the induction nozzle $X = 1.0$ mm and the length of the acceleration tube L_a is 50 mm are given in Table 4.

Table 4 Velocity of air flow in the nozzle

POSITION	D_2 (mm)	V (m/s)
IN INDUCTION NOZZLE	1.5	154
	3.0	116
IN ACCELERATED TUBE	1.5	96
	3.0	123

D_2 : BORE OF INDUCTION NOZZLE
 V : AIR VELOCITY

3.2 Yarn tension in the nozzle

The yarn tension induced along the air flow is calculated as;

$$F = (1/2) \cdot C_f \cdot \rho \cdot V^2 \cdot \pi \cdot d \cdot l \dots \dots \dots (11)$$

where l is the yarn length in the jet nozzle and in air-jet, and the air drag coefficient C_f is given by

$$C_f = K \cdot R_{ea}^n = K \cdot [V \cdot (d/2)/\nu]^n \dots \dots \dots (12)$$

where R_{ea} is Reynolds number whose dimension in length is the yarn radius, ν is the kinematic viscosity of air. K and n are the coefficients that represent the air drag, and vary with the kinds of yarns used. They are measured by the experimental apparatus similar to the apparatus used by J. Gold et al^[8]. These values are tabulated in Table 5. Substituting eq. (12) into eq. (11), we obtain

$$F = \frac{1}{2^{n+1}} \cdot K \cdot \nu^{-n} \cdot \rho_0 \cdot \frac{Q_E}{A} \cdot V^{n+1} \cdot \pi \cdot d^{n+1} \cdot l \dots \dots \dots (13)$$

Table 5 K and n to calculate air drag coefficient C_f

SPECIMEN	tex	K	n
NYLON MONOFILAMENT	16.8	2.34×10^{-3}	0.17
	28.2	6.96×10^{-3}	-0.04
COTTON	7.4	6.98×10^{-1}	-0.47
	9.8	3.53×10^{-1}	-0.35
	19.7	5.43×10^{-2}	-0.06
POLYESTER MULTIFILAMENT	27.8	3.83×10^{-2}	-0.18

$C_f = K \cdot R_{ea}^n$
 K, n : VALUES DECIDED BY SPECIMEN
 R_{ea} : RADIUS REYNOLDS NUMBER

4. Results and Discussion

4.1 Air flow in the nozzle

Figure 4 shows the relation between driving flow rate Q_1 and induced flow rate Q_2 for $L_a=0$. Q_1 and Q_2 vary with driving pressure p_v , bore of the induction nozzle D_2 , the amount of retreatment of the induction nozzle X . In Fig. 4(a), the relations are shown with parameter D_2 . It shows that larger D_2 induces larger Q_1 at the same Q_2 . From this, it is clear that the larger D_2 is, the more effectively it induces the induced flow f_2 within the limit of this experiment. In this experiment, $D_2=3.0$ mm is the maximum inner bore from the dimensional limitations of the outside diameter of the induction nozzle. Figure 4(b) emphasizes the effect of p_v on Q_1 and Q_2 in the case of $D_2=3.0$ mm. Q_1 can be increased with increasing X at the same p_v . This figure shows that both Q_1 and Q_2 increase with p_v until Q_2 reaches a certain value and it will not increase any more even if Q_1 increases.

The efficiency of power consumption is high when p_v is small, and the larger $Q_2/Q_3 (=Q_2/(Q_1+Q_2))$ is, the larger the tension becomes as described in section 4.3. From Figs. 4(a) and (b), therefore, Q_2/Q_3 is the maximum at $D_2=3.0$ mm and $Q_1=2.0 \times 10^{-3}$ m³/s² in this experiment.

(a) Parameter is bore of induction nozzle D_2

(b) Parameter is driving pressure p_v ($D_2=3.0$ mm)

Fig. 4 Relation between driving flow rate and induced flow rate

Fig. 5 Yarn tension driven in the nozzle and jet
Parameter is length of acceleration tube
($p_v=1.0$ atg, $D_2=3.0$ mm, $X=1.0$ mm, Nylon-monofilament yarn 16.8 tex, yarn length in jet=200 mm)

4.2 Effect of length of the acceleration tube

Figure 5 shows the relation between the yarn tension driven in the nozzle and the length of the acceleration tube in the case of $p_v=1.0$ atg, $D_2=3.0$ mm, $X=1.0$ mm and nylon-monofilament yarn 16.8 tex. Both F_0 and F_{200} increase with the length of the acceleration tube L_a within the limit of this experiment. However the largest F_{jet} appears when the tube 100 mm in length is installed because the increase in F_0 with L_a becomes larger than the one in F_{200} . So in the case that L_a is larger than 100 mm, the air velocity in jet (during 200 mm from the tip of the nozzle) might decrease by the effect of the friction loss in the tube.

4.3 Yarn tension in the nozzle

The yarn tension in the nozzle is shown in Fig.6 for each kind of yarn in the case of $p_v=1.0$ atg, $L_a=50$ mm and $X=1.0$ mm. The horizontal axis is the yarn length inserted into the nozzle from the entrance of the induction nozzle. The solid lines ($D_2=1.5$ mm) and dotted lines ($D_2=3.0$ mm) in this figure are obtained from numerical calculation mentioned in the preceding section. From this calculation, smaller D_2 induces higher air velocity (see Table 4) in the induction nozzle (L is less than 36 mm). Therefore, the yarn tension with $D_2=1.5$ mm is larger than the tension with $D_2=3.0$ mm. However when the yarn tip emerges from the induction nozzle, the yarn tension with $D_2=3.0$ mm increases more than the tension with $D_2=1.5$ mm because the air velocity in the mixing area is larger than the tension with $D_2=1.5$ mm, and in the acceleration tube the yarn tension with $D_2=3.0$ mm becomes larger than the tension with $D_2=1.5$ mm. This tendency is also shown by the experimental data plotted by open circles ($D_2=1.5$ mm) and solid circles ($D_2=3.0$ mm) in the same figure.

For cotton and nylon-monofilament yarns, the experimental values agree well with the theoretical results. Though further examples are omitted here, close agreement between experimental and calculated values was

Fig. 6 Yarn tension in the nozzle ($p_v=1.0$ atg, $L_a=50$ mm, $X=1.0$ mm)

Bore of induction nozzle=1.5 mm

→ Experimental value ○

→ Theoretical value

Bore of induction nozzle=3.0 mm

→ Experimental value ●

→ Theoretical value

obtained for other fineness yarns. Thus it is considered that experimental results can be explained well by this theory.

In the case of polyester multifilament yarns, good agreement of both values is obtained so far as the yarn tip is in the induction nozzle. In the mixing area, however, experimental values become much larger than the theoretical yarn tensions. This is thought to arise from the cause that F enlarges in the mixing area where the bore of the flow becomes large because each filament that makes up a yarn disperses in threads.

5. Conclusions

The results obtained were as follows.

- 1) An increase of the bore size of the induction nozzle provided in the jet nozzle increases the air flow induced by driving flow. The maximum bore size was 3 mm in this experiment.
- 2) The induced flow rate reached a limited value in spite of increasing the driving pressure.
- 3) The yarn tension induced in a jet reached a limited value in spite of increasing the length of the acceleration pipe.
- 4) The yarn tension calculated from equations based on the isentropic flow of compressible fluid and the air drag in the nozzle were in agreement with those obtained

experimentally.

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