Dynamics analysis and testing in air-jet weft insertion

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Received 13 March 2006; revised received and accepted 11 August 2006

On the basis of fluid dynamics, this paper deduces the pull force formula of main nozzle on air-jet loom and introduces a method of experiment to test the airflow velocity in the exit of nozzle. The effect of different structure parameters of main nozzle on the pull force has been studied. It is observed that the inlet of thread tube is a bottleneck of main nozzle and the main development of main nozzle lengthens the thread tube. The theoretical findings are found to be in good agreement with experimental findings and this verifies that the formula for pull force is reasonable.

Keywords: Air-jet loom, Dynamics analysis, Weft insertion
IPC Code: Int. Cl. D03D

1 Introduction
The idea of air-jet weft insertion has been known for almost one hundred years. However, airflow from a nozzle tends to diffuse very rapidly and hence the air-jet loom brings into commercial machine just only about thirty years ago. To improve airflow efficiency, several kinds of weft insertion systems have been developed. There are three main sorts, namely the air guide system, the profiled reed with sub-nozzle system, and the air guide with sub-nozzle system. Many researchers have studied the quantitative analysis method with different paths on air-jet weft insertion of air-jet loom. In spite of several decades of intensive research, there are always some differences between calculated and measured values because of the varieties of friction coefficient of yarn, nozzle shape and working accuracy of nozzle wall which make the theoretical arithmetic to get differently. This paper reports the theoretical analysis and study on how each parameter of main nozzle affects the pull force (PF) of airflow on weft.

2 Materials and Methods

2.1 Structure Analysis of Main Nozzle
Reynolds number is about $10^6$ when main nozzle of air-jet loom is filling. The value is far above the boundary of laminar flow. Therefore, the airflow of air-jet weft insertion is the turbulent flow with low press, small quantity flow and subsonic velocity. Figure 1 shows a kind of main nozzle structure.

Compressed air flows from main tank to main nozzle through airflow inlet. At first, main nozzle accelerates airflow to location sonic velocity. This part is named airflow acceleration zone. It consists of the first air chamber, rectifier tank, second air chamber and throat. The first air chamber is cyclic, air flows along axis and circle when it comes into the first air chamber and comes into being high-speed eddy flow. Rectifier tank has many grooves along circle. The high-speed eddy flow can be adjusted to become direct current when it passes through rectifier tank. The second air chamber is cyclic also, airflow can be accelerated and becomes subsonic axial flow. Throat is the minimum section of the circle gap, airflow reaches sonic velocity when it passes throat.

![Single channel main nozzle structure](image)

Fig. 1 — Single channel main nozzle structure [A — nozzle body, B — nozzle needle, C — thread tube, D — weft inlet, a — airflow inlet, b — first air chamber, c — rectifier tank, d — second air chamber, e — throat, f — nozzle needle exit, and g — weft acceleration zone]
Thread tube is a constant section pipe. When air flows into thread tube from nozzle needle exit, the static pressure of airflow is far below atmospheric pressure. With the effect of negative pressure, weft can enter thread tube from weft inlet, then it is accelerated in thread tube. Hence, various structure parameters of main nozzle which affect PF have been analyzed. The main nozzle is divided into following three assembled tubes (Fig. 1):

**Tube A** — A convergent-divergent nozzle outside of main nozzle needle.
**Tube B** — A converging nozzle inside of main nozzle needle.
**Tube C** — A cylindrical tube of thread tube.

### 2.1.1 Structure Analysis of Tube A and Pressure Calculation of Exit

This tube belongs to convergent-divergent nozzle. Airflow can be accelerated at the convergent tube, and then it reaches sonic at the throat. The exit is a sudden expansion zone where energy loss exists. For compressible flow, there are some difficulties in computational analysis without experiment. Oh et al. analyzed the airflow speed and pressure at the exit by simulation software and pointed out that the airflow speed is sonic at the throat. The exit pressure is always equal to the exit pressure of tube A. Here, weft is pulled and it enters thread tube. On the basis of the theory of constant section adiabatic flow friction tube, airflow velocity leans

\[
\frac{A_{A2}}{A_1} = \frac{1}{M_{A2}^2} (\frac{2}{\gamma} + 1) + \gamma - 1 \frac{1}{2} M_{A2}^2 \frac{\gamma - 1}{\gamma} \frac{\gamma}{\gamma - 1}
\]

\[
\frac{P_{A1}}{P_{A2}} = \frac{\gamma}{\gamma - 1} M_{A2}^2 \frac{\gamma - 1}{\gamma} \frac{\gamma}{\gamma - 1}
\]

where \(A_{A2}\) is the cross-sectional area of tube A exit; \(A_1\), the cross-sectional area of throat; \(M_{A2}\), the Mach number of airflow at tube A exit; \(\gamma\), the adiabatic coefficient (=1.4); \(P_{A1}\), the inlet pressure of tube A; and \(P_{A2}\), the exit pressure of tube A.

Because the cross-sectional area of tube A exit and the cross-sectional area of throat are known, \(M_{A2}\) and \(P_{A2}\) can be calculated. For convenient analysis, a kind of nozzle size is considered to illustrate the effect of exit pressure of tube A on tube B [\(A_1=3.016 \times 10^{-6} \text{ m}^2, A_{A2}=12.5664 \times 10^{-6} \text{ m}^2\) and \(P_{A1}=0.3 \text{ MPa}\)].

The solution of Eq. (1) can be derived (\(P_{A2} = 8.378 \text{ kPa}\)). Obviously, the pressure of nozzle needle exit is far lower than that of nozzle needle inlet; the negative pressure sucks outside air into tube B. In practice, supplied pressure of main nozzle \((P_0)\) ranges from 0.2 MPa to 0.4 MPa and the exit pressure \((P_{A2})\) ranges from 5.585 kPa to 11.17 kPa. It satisfies the demand of negative pressure to tube B.

### 2.1.2 Structure Analysis of Tube B and Airflow Speed Calculation

This tube may be regarded as a composite tube that consists of an isentropic flow converging nozzle and a constant section friction tube. Figure 2 shows an amplified schematic diagram of main nozzle needle. Airflow is accelerated in converging tube, but its velocity cannot exceed sonic velocity. Whether it reaches sonic velocity, it depends on the length of cylindrical tube. Before airflow velocity arrives at sonic velocity, the air pressure of the exit is invariable, which always equals to the exit pressure of tube A. Here, weft is pulled and it enters thread tube. On the basis of the theory of constant section adiabatic flow friction tube, airflow velocity leans

![Fig. 2 — Schematic diagram of main nozzle needle](image-url)
toward sonic velocity. For subsonic airflow in the inlet, airflow is accelerated in the cylindrical tube. In contrast, for supersonic airflow in the inlet, the airflow is decelerated in the cylindrical tube.

Now consider cross-section, which connects the converging tube and cylindrical tube as section 1 and the parameters of section 1 are marked with subscript 1. Consider the exit cross-section as section 2 and the parameters of section 2 are marked with subscript 2. Stagnation point is atmosphere that is marked with subscript 0. According to the fundamental equation of fluid mechanics\(^7,8\), following relationships are obtained:

\[
P_0 \frac{\gamma}{\gamma - 1} \frac{1}{2} M_{1}^{\gamma - 1} \frac{\gamma + 1}{2} \ln \left( \frac{M_{2}^{\gamma}}{M_{1}^{\gamma}} \right)
\]

\[
P_0 \frac{\gamma}{\gamma - 1} \frac{1}{2} M_{2}^{\gamma - 1} \frac{\gamma + 1}{2} \ln \left( \frac{M_{2}^{\gamma}}{M_{2}^{\gamma}} \right)
\]

\[
4 \mu_L L B = \frac{\gamma + 1}{2} \ln \left( \frac{M_{2}^{\gamma}}{M_{1}^{\gamma}} \right) + \frac{\gamma + 1}{2} \left( \frac{\gamma - 1}{\gamma} \right) \frac{M_{2}^{\gamma} - M_{1}^{\gamma}}{2 \mu_L}
\]

\[
\frac{4 \mu_L L B}{D_B} = \frac{\gamma + 1}{2} \ln \left( \frac{M_{2}^{\gamma}}{M_{1}^{\gamma}} \right) + \frac{\gamma + 1}{2} \left( \frac{\gamma - 1}{\gamma} \right) \frac{M_{2}^{\gamma} - M_{1}^{\gamma}}{2 \mu_L}
\]

where \(\mu_B\) is the frictional coefficient between the airflow and the nozzle wall; \(L_B\), the length of cylindrical tube; and \(D_B\), the inner diameter of cylindrical tube.

The system of Eq. (2) is nonlinear equations in which parameters \(P_{B1}, M_{B1}\), and \(M_{B2}\) are unknown. They can be solved by numerical approximation.\(^9\) The function of converging tube is convenient for threading. Weft is pulled in the cylindrical tube of length \(L_B\). If the inlet and exit velocities of cylindrical tube are known, the PF can be found out. Owing to its similarity with tube C, the analysis of PF is given in section 2.2.1.

2.1.3 Structural Analysis of Tube C and Airflow Speed Calculation

This tube is a constant section adiabatic flow friction tube (Fig. 1). The exit of tube A and tube B is the inlet of tube C. Airflow of the inlet comes into being coaxial double round tube fluid, which include shock wave and expand wave. It is difficult to find out the inlet velocity of tube C. According to the previous experiment\(^6\), both airflows will be mixed and trend to coherence at 5-10 times the length of the diameter of thread tube. The airflow velocity falls to 0.5 Mach number because volume expands. The exit velocity can be listed by following experimentation, and then the inlet speed of tube C can be solved from the following equation:

\[
\frac{4 \mu_L L C}{D_C} = \frac{\gamma + 1}{2} \ln \left( \frac{M_{C2}^{\gamma}}{M_{C1}^{\gamma}} \right) + \frac{\gamma + 1}{2} \left( \frac{\gamma - 1}{\gamma} \right) \frac{M_{C2}^{\gamma} - M_{C1}^{\gamma}}{2 \mu_L}
\]

When air flows with subsonic velocity, an increase in supplied pressure leads to an increase in the airflow velocity and the pressure of thread tube. But the exit pressure of tube C is changeless and equals to atmospheric pressure. When an increase in supplied pressure which leads to the exit pressure of tube C arrives at sonic velocity, if supplied pressure continues to increase, the exit velocity cannot increases, but the exit pressure increases. Hence, PF also increases. Because air-jet loom always works in the subsonic velocity, the exit pressure of tube C is considered to be a constant. It is similar to tube B and airflow is accelerated in thread tube. Because tube C is longer than tube B, weft gets larger PF in tube C than that in tube B.

2.2 Dynamics Analysis of Air-jet Weft Insertion in Main Nozzle

2.2.1 PF Analysis

PF can be divided into force \(F_1\) in the friction tube of tube B and force \(F_2\) in the friction tube of tube C:

\[
F + F_1 + F_2
\]

At first, let us analyze the force of an infinitesimal yarn. A random tiny yarn of length \(dl\) (Fig. 3) was chosen, considering weft movement along axis. The PF of the tiny yarn\(^10\) is:

\[
dF = \frac{1}{2} \rho \pi d (v - u) \, dl
\]

Fig. 3 — Schematic diagram of the force on an infinitesimal yarn
where $F$ is the PF; \( \rho_f \), the air-drag coefficient; \( \rho \), the airflow density; \( d \), the yarn diameter; \( v \), the airflow velocity; \( u \), the yarn velocity; and \( l \), the yarn length in the main nozzle.

Stagnation points of tube B and tube C are different from tube A. The stagnation temperature is equal to the temperature of environment. According to state equation, energy equation and continuity equation of stationary monadic constant entropy flow gas, the following relationship is obtained:

\[
20022 \rho \rho p T v v u u = \ldots (6)
\]

where \( T \) is the temperature of airflow; \( T_0 \), the temperature of environment; \( C_p \), the ratio of specific heats; \( R \), the gas constant (287); \( \rho \), the air density; and \( v_2 \), the airflow velocity of exit.

The air density (\( \rho \)) of random section can be derived as follows:

\[
\rho = \frac{P_2 v_2}{R v (T_0 - v_2^2/2C_p)} \ldots (7)
\]

where \( P_2 \) is the air pressure of exit.

Because of the friction between pipe wall and airflow, the airflow velocity changes along pipe. Owing to the length of main nozzle being not longer, the cross-section is small and the dissipation of heat is ignored. The gas that flows in pipe can be considered as adiabatic process. Based on gas dynamics atomic formulas for infinitesimal \( dl \), the following differential equation of the airflow velocity along axis is obtained:

\[
\frac{4\mu}{D} dl = \frac{1 - M^2}{M^4 \gamma (1 + M^2 (\gamma - 1)/2)} dM^2 \ldots (8)
\]

where \( M \) is the airflow Mach number; and \( D \), the inner diameter of main nozzle.

By substituting Eqs (7) and (8) into Eq. (5), the PF of the tiny yarn can be expressed as follows:

\[
dF = \frac{\pi d DP_2 \rho_f (cM - u)^2 (1 - M^2)}{8M^2 \mu R (T_0 - M^2 c^2/2C_p)(1 + M^2 (\gamma - 1)/2)} dM^2 \ldots (9)
\]

where \( c \) is the sonic velocity.

Owing to main nozzle being short, let us consider that \( \rho_f \) is a constant and does not change with air velocity. Here, Matlab software was adopted to process symbolic integration and the integrating range is \([M_1, M_2]\), as explained by the following equation:

\[
F = \frac{\pi d DP_2}{4\mu R \gamma (T_0 - M^2 c^2/2C_p)} \Phi_{i+1} - \Phi_i \ldots (10)
\]

Here,

\[
\Phi_i = (1 + \gamma)cu \ln(M_i) + (1 + \gamma)u^2/2 - c^2 \gamma M_i
\]

\[
+ cu/M_i^2 - u^2/3M_i^3 - (1 + \gamma)cu \ln(1 + M_i/5)/2
\]

\[
- \sqrt{5} \arctan(M_i/\sqrt{5})((1 + \gamma)c^2/2 - (1 + \gamma)cu/2
\]

\[
- (1 + \gamma)u^2/10)
\]

where \( \Phi_i \) is an integral polynomial and can be considered a nondimensional variable; \( I = 1, 2 \); \( M_1 \), the Mach number of inlet ; and \( M_2 \), the Mach number of exit.

It can be observed from Eq. (10) that PF is directly related to \( d \) & \( \rho_f \) and is inversely related to \( \mu \). Because the length and diameter of thread tube are correlated with \( M_1 \) & \( M_2 \), they also influence PF. The force \( F_1 \) can be obtained from Eq. (10). In contrast, the air inlet velocity of tube C is unknown and to obtain the solution of \( F_2 \), some experiments are required.

### 2.2.2 Air Speed of Inlet and Exit of Tube C

To calculate PF by Eq. (10), Mach number is required which is in the inlet and exit of nozzle. Laser Doppler Tester was used to measure the airflow speed in tube C exit. The merits of the tester are non-contact measurement and it does not disturb the flow field. Here, three-dimensional LDV system of TSI is used, which includes a 5W laser, IFA755 (Digital Burst Correlator), COLOR2LINK (Multicolor Receiver Model 9230) and COLORBURST (Multicolor Beam Separator Model 9201). Figure 4 shows the work principle of Laser Doppler Tester.

Table 1 shows the measured results of airflow velocity in the exit of tube C with different supplied pressure. By substituting it into Eq. (3), the airflow velocity.
velocity in the inlet of tube C can be obtained (Table 1). Table 2 shows the air pressure in the exit of tube A and the inlet/exit Mach number in the cylindrical tube of tube B, which was calculated by using Eqs (1) and (2). In this experiment, the testing conditions are: $D_C = 0.004$ m, $L_C = 0.22$ m, $\mu_C = 0.004$, $D_B = 0.0025$ m, $L_B = 0.022$ m, $\mu_B = 0.0025$, $P_0 = 1.01 \times 10^5$ Pa, $C_p = 1004.6$ J/kg K, and $A_s = 3.016 \times 10^{-6}$ m$^2$.

It can be observed from the experimental results that the airflow velocity in the inlet of tube C drops rapidly after both airflows mixing, even though the airflow velocity in the exit of tube A and tube B exceed sonic velocity. Hence, how to optimize the structure of main nozzle is a worthy of further work.

### Table 1—Supplied pressure and air velocity in the inlet / exit of tube C

<table>
<thead>
<tr>
<th>Supplied pressure $\times 10^6$, Pa</th>
<th>Mach number in the exit of tube C $(M_{C2})$</th>
<th>Mach number in the inlet of tube C $(M_{C1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.335</td>
<td>0.311</td>
</tr>
<tr>
<td>0.15</td>
<td>0.457</td>
<td>0.397</td>
</tr>
<tr>
<td>0.20</td>
<td>0.608</td>
<td>0.470</td>
</tr>
<tr>
<td>0.22</td>
<td>0.661</td>
<td>0.488</td>
</tr>
<tr>
<td>0.25</td>
<td>0.746</td>
<td>0.507</td>
</tr>
<tr>
<td>0.28</td>
<td>0.791</td>
<td>0.514</td>
</tr>
<tr>
<td>0.30</td>
<td>0.826</td>
<td>0.518</td>
</tr>
<tr>
<td>0.32</td>
<td>0.853</td>
<td>0.520</td>
</tr>
<tr>
<td>0.35</td>
<td>0.896</td>
<td>0.523</td>
</tr>
<tr>
<td>0.38</td>
<td>0.928</td>
<td>0.524</td>
</tr>
<tr>
<td>0.40</td>
<td>0.951</td>
<td>0.525</td>
</tr>
<tr>
<td>0.43</td>
<td>1.000</td>
<td>0.525</td>
</tr>
</tbody>
</table>

### Table 2—Supplied pressure and air velocity in the inlet/exit of tube B

<table>
<thead>
<tr>
<th>Supplied pressure $\times 10^6$, Pa</th>
<th>Air pressure in the exit of tube A $(P_{A2}) \times 10^3$, Pa</th>
<th>Mach number in the cylindrical tube inlet of tube B $(M_{B1})$</th>
<th>Mach number in the cylindrical tube exit of tube B $(M_{B2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>2.793</td>
<td>0.6572</td>
<td>1</td>
</tr>
<tr>
<td>0.15</td>
<td>4.189</td>
<td>0.6600</td>
<td>1</td>
</tr>
<tr>
<td>0.20</td>
<td>5.585</td>
<td>0.6628</td>
<td>1</td>
</tr>
<tr>
<td>0.22</td>
<td>6.144</td>
<td>0.6640</td>
<td>1</td>
</tr>
<tr>
<td>0.25</td>
<td>6.982</td>
<td>0.6658</td>
<td>1</td>
</tr>
<tr>
<td>0.28</td>
<td>7.820</td>
<td>0.6676</td>
<td>1</td>
</tr>
<tr>
<td>0.30</td>
<td>8.378</td>
<td>0.6688</td>
<td>1</td>
</tr>
<tr>
<td>0.32</td>
<td>8.937</td>
<td>0.6701</td>
<td>1</td>
</tr>
<tr>
<td>0.35</td>
<td>9.775</td>
<td>0.6720</td>
<td>1</td>
</tr>
<tr>
<td>0.38</td>
<td>10.612</td>
<td>0.6740</td>
<td>1</td>
</tr>
<tr>
<td>0.40</td>
<td>11.171</td>
<td>0.6753</td>
<td>1</td>
</tr>
<tr>
<td>0.43</td>
<td>12.009</td>
<td>0.6774</td>
<td>1</td>
</tr>
</tbody>
</table>

### 2.2.3 PF Testing

According to Bernoulli’s equation, the experimental method was designed as shown in Fig. 5. Compressed air passes through the regulating valve and gas enters into main nozzle through solenoid valve by computer control. One side of the weft extends into main nozzle and another connects with load cell. The signal is sent via A/D conversion to computer where data is saved and processed. Because the initial velocity of yarn is equal to zero, the tested tension is the beginning of weft insertion.

The pull force of two types of yarns with different conditions was observed. It is found that the diameter $(d)$ and air-drag coefficient $(\rho_f)$ are $1.395 \times 10^{-4}$ m & $1.881 \times 10^{-4}$ m and $0.026$ & $0.033$ for 13tex cotton and 13×2tex T/C [65/35] respectively. Pull force can be observed according as Eq. (10).

### 3 Results and Discussion

The relationships between various parameters and PF are given as follows.

**Supplied Pressure and PF**

Supplied pressure is an important craft parameter of weft insertion. An increase in supplied pressure leads to an increase in the airflow velocity. Table 3 shows the measured and calculated values of pull force with different pressures. Figure 6 shows the curve of the measured results and calculated results of cotton yarn and T/C yarn. It is found that the calculations are in good agreement with observations and hence Eq. (10) is able to reflect the influence of air velocity on PF. An increase in airflow velocity leads to an increase in PF. Furthermore, Table 3 shows that the PF that comes from tube B is dominant when supplied pressure is low; however, PF that comes from tube C is dominant when the supplied pressure exceeds 0.2MPa, i.e. when the air velocity exceeds 200m/s, the pull force of tube C will exceed that of tube B. From the calculated results, one can observe that the
pull force of tube B decreases a little with the increase in supplied pressure, but the difference is small. Hence, the pull force of thread tube is dominant.

Yarn Speed and PF

The velocity gradient between airflow and weft affects pull force. From the beginning of weft insertion, an increase in the velocity of weft leads to a decrease in the difference of speed between weft and airflow, so it also leads to a decrease in the pull force. In order to eliminate the influence of yarn material, let $\Psi = \Phi_2 - \Phi_1$ [Eq.(10)]. $\Psi$ is a nondimensional variable. Figure 7 shows the result of $\Psi$ with air pressure of 0.25 MPa and 0.35 MPa. It is obvious that $\Psi$ decreases with the increase in air speed.

Main Nozzle Length and PF

By changing yarn length in main nozzle, the PF at 0.3MPa of supplied pressure was observed. Figure 8 shows the measured and calculated values of pull force with different lengths. Obviously, the PF is directly related to yarn length.

Table 3 — Measured and calculated values of pull force with different pressures

<table>
<thead>
<tr>
<th>Supplied pressure $\times 10^6$, Pa</th>
<th>13tex cotton</th>
<th>13×2tex T/C</th>
<th>13×2tex T/C</th>
<th>13×2tex T/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_2$</td>
<td>$F_1$</td>
<td>$F$</td>
<td>$F_2$</td>
</tr>
<tr>
<td>0.10</td>
<td>0.0189</td>
<td>0.0542</td>
<td>0.0731</td>
<td>0.0324</td>
</tr>
<tr>
<td>0.15</td>
<td>0.0340</td>
<td>0.0530</td>
<td>0.087</td>
<td>0.0581</td>
</tr>
<tr>
<td>0.20</td>
<td>0.0584</td>
<td>0.0519</td>
<td>0.1103</td>
<td>0.0999</td>
</tr>
<tr>
<td>0.22</td>
<td>0.0673</td>
<td>0.0514</td>
<td>0.1188</td>
<td>0.1152</td>
</tr>
<tr>
<td>0.25</td>
<td>0.0835</td>
<td>0.0507</td>
<td>0.1343</td>
<td>0.1430</td>
</tr>
<tr>
<td>0.28</td>
<td>0.0921</td>
<td>0.050</td>
<td>0.1422</td>
<td>0.1577</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0990</td>
<td>0.0496</td>
<td>0.1485</td>
<td>0.1694</td>
</tr>
<tr>
<td>0.32</td>
<td>0.1045</td>
<td>0.0491</td>
<td>0.1536</td>
<td>0.1789</td>
</tr>
<tr>
<td>0.35</td>
<td>0.1128</td>
<td>0.0484</td>
<td>0.1611</td>
<td>0.1930</td>
</tr>
<tr>
<td>0.38</td>
<td>0.1193</td>
<td>0.0476</td>
<td>0.1669</td>
<td>0.2042</td>
</tr>
<tr>
<td>0.40</td>
<td>0.1235</td>
<td>0.0471</td>
<td>0.1707</td>
<td>0.2114</td>
</tr>
<tr>
<td>0.43</td>
<td>0.1336</td>
<td>0.0463</td>
<td>0.1799</td>
<td>0.2286</td>
</tr>
</tbody>
</table>

Fig. 6 — Relationship between supplied pressure ($P$) and PF ($F$)

Fig. 7 — Relationship between yarn speed ($v$) and PF ($\Psi$)
4.1 Structure of main nozzle and working accuracy of nozzle are important to PF. The decrease in diameter of main nozzle can reduce energy consumption and the increase in length of thread tube can increase PF. Due to the high speed trend of air-jet loom, it is the main development of main nozzle to lengthen thread tube or series nozzles.

4.2 Inlet of thread tube is a bottleneck of main nozzle, where air speed decreases very rapidly.

4.3 Theoretical findings are in good agreement with the experimental findings and this verifies that the formula for the pull force is reasonable.

4.4 There are some errors in the data of experiment, but the tendency is correct. Because air velocity of the exit needs measure in the theories calculation method, it still cannot deduce the pull force absolutely according to the structure size of nozzle.

4 Conclusions

**Thread Tube Diameter and PF**

Diameter of thread tube affects air velocity of the inlet and exit and the pull force. Figure 9 shows numerical solution of pull force with φ 4-8mm. It is obvious that the increase in diameter causes an increase in pull force. But the air consumption increases. It should be avoided in design.

**Frictional Coefficient between the Airflow and Yarn**

It can be seen from Eq.(10) that the increase in frictional coefficient μ leads to a decrease in PF. Hence, the nozzle wall must be made very smoothly to avoid energy loss.

References