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Modeling and Analysis of Compressed Air Consumption of Air Jet Loom

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Abstract — *Air-jet looms popularized in the textile industry in mass scale production due to high speed of weft insertion, which leads to higher productivity with greater efficiency. The air jet looms provide best quality for cotton and cotton based fabrics, the manner in which the weft is inserted. However, due to higher compressed air consumption, production cost of weaving on air-jet looms is comparatively high and hence less preferred to be in production despite its high production speed especially in countries like Sri Lanka, where the energy cost is prohibitively high. The compressed air consumption is highly depend on the weft yarn parameters and the width of the fabric. The compressed air pressure setting for different fabrics done on trial and error basis and hence the running cost may not be optimized in addition to the raw material wastage in setting up the loom. The authors attempt to develop a mathematical model for the air consumption and the tractive force taken into account the parameters of the weft yarn and the mechanical settings of the loom. The model was verified with experimental results and has shown that there is a good agreement exists between the theoretical and experimental results and thereby verified the accuracy of the model*

Keywords — *Mathematical modelling, air jet loom, compressed air consumption, different weft yarns.*

I. INTRODUCTION

Weaving is one of the fabric production processes comprising interlacement of warp and weft yarns on a weaving machine commonly known as looms. The evolution of weaving was embarked with a manual weaving technique which used a shuttle to insert weft yarn. Subsequently semi automatic weaving machines were invented with a considerable increase in productivity. However, with the advent of technology an automatic power looms were developed and it played a pivotal role in weaving. Since the dynamics of shuttle and its dimensions were identified as a barrier for the productivity improvement in power looms as a breakthrough invention, shuttle less looms were developed. On the basis of weft insertion mechanism, shuttle-less looms are further classified into projectile, rapier, water-jet, and air-jet looms. In water jet looms, the fabric become wet as well as due to high water consumption, thus creating serious limitations in its usability such as imposing restrictions of weaving 100% cotton and cotton blend fabrics on water jet looms. However, air jet looms do not suffer from such limitations and hence it inevitably becomes one of the leading, successful and highest productive weaving machines. Air-jet looms have become quite popular in the textile industry in mass scale due to their high productivity and better controllability [12]. In the countries having higher energy cost does not prefer air-jet weaving machines as compared to projectile weaving machines or rapier looms despite their high production speed [7]. The air-jet weaving is the most productive but also most energy consuming weaving method [2]. If it is expressed in quantitative terms, production rate of air jet machines are as high as 1,100 weft insertions per minute covering a wide range of processing yarns like spun and continuous filament yarns while the average specific energy consumption ranges from 3 to 5 kWh/kg at a weft insertion rate of 2,000 m/min [1]. The largest share of energy consumption in air jet looms is due to the pneumatic components specifically through the relay nozzles of the air-jet loom which amount up to 80% of the energy [4]. When hundreds of air jet looms run in a textile factory, energy consumed to generate required amount of compressed air is considerably high and improving compressed air system efficiency is also of key importance [8]. So the reduction of energy losses within the pneumatic infrastructure grabs the attention of the researchers. In a model-based approach, an extended Kalman filter was implemented and used it for the topology optimization with a better understanding of the loss sources and possible improvement strategies [10]. Only auto drains, filters and refrigeration dryers are used to reduce the water vapor content compressed air used for weaving in contrary to the use of desiccant dryers in knitting where low relative humidity (RH) is crucial.

As such researchers as well as machine manufacturers have continuously been engaged in enhancing the efficiency of air-jet weft insertion to its maximum, though it is a challenging task. In the plethora of literature on factors affecting the compressed air consumption of air jet looms, fabric width was found to be the most dominant factor followed by loom speed, reed count, and weft yarn count respectively. A statistical model for predicting the compressed air consumption on air-jet loom was developed so that it can be used for optimizing the production planning [11]. Despite of manufacturing the same quality of fabrics on machines with same model and make, air consumption was varying [7].

Attempts made by the researcher to introduce sophistications to the nozzles found in literature as a means of achieving higher efficiency in air jet weaving. At ITA, a new nozzle geometry called High-Volume-Low-Pressure nozzle (HVLP nozzle) were developed based on convergent nozzle aerodynamic theory to successfully save energy up to 30% [1]. A profiled reed provides guidance for the air so that a nozzle catches and stretches the yarn at the right side of the machine to mark the end of weft insertion [3]. A novel method based on energy balances has been applied to optimize the energy costs while keeping constant fabric quality [4]. The present relay nozzles, available on the market, are operating at a pressure of approximately 3-5 bar, depending on the yarn and the type of nozzle and providing an average yarn velocity across the shed of 55-80 m/s. Masuda et al. [13] developed a new supplementary apparatus, which mechanically assists the weft insertion, in view of reducing the compressed air consumptions and thereby the energy by quantities from 10 to 30 % with the new apparatus. Ishida and Okajima [14, 15] and Jeong et al. [16] developed a better nozzle design to improve the efficiency of the air-jet during weft insertion and to reduce air consumption. The air consumption could be reduced by 21% achieved by decreasing the hole diameter of single-holed relay nozzle and by optimizing the blowing time of multi-holed relay nozzles [17]. Belforte et al. [18] analyzed the effect of different sub-nozzle geometries on pneumatic weft insertion and compressed air consumption. The effective inter-relay nozzles distance was found to be 70 mm to 75 mm with the variation of the machine and the produced material [5].

Effect of yarn parameters on the optimization of compressed air consumption was also under serious investigation The yarn linear density, structure, and twist are considered the main factors affecting the suitability of pneumatic weft insertion [19]. The yarn twist direction found to be had no significant impact on weaving [20]. The yarn velocity has a positive correlation with contact surface the air [21]. The fiber quality as well as yarn production parameters were found to have significant influence on the weft yarn insertion speed and with respect to the yarn properties in the studies of Githaiga et al. [22]. Kayacan et al. [6] investigated the effect of yarn parameters on the weft yarn velocity.

The friction between the weft yarn and the air flow exerts the drag (tractive force) force which causes the weft yarn to be ejected at high speed. The dynamics of the type P air jet weaving machines and the definition of the skin friction coefficient for multifilament weft were studied with theoretical calculations [9]. Further, tandem nozzles have been devised to reduce the air consumption of air jet looms.

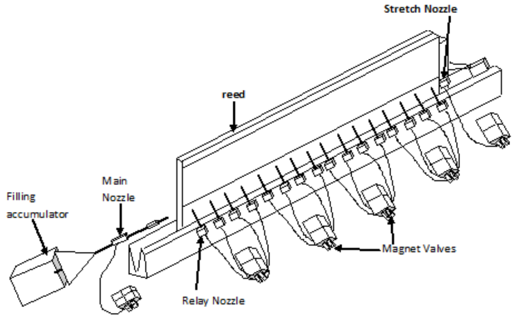
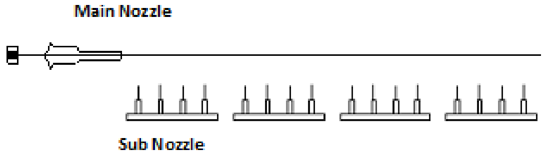


Fig. 1 (a)



Group 1 Group 2

Group 3 Group 4

Nozzle Arrangement

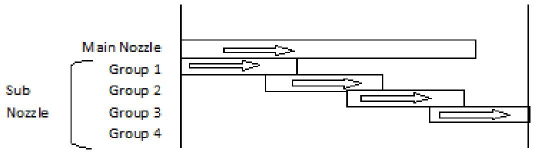


Fig 1 (b)

Fig.1: (a) Sub nozzles in group operation (b) sub nozzle group timing

Figure 1 shows how 16 number of sub nozzles in air jet loom is operated in four groups. The timing of the relay nozzle groups can be varied such that there is an overlap in timing of consecutive groups so that weft yarn is accelerated while avoid dropping due to the gravitational force.

In this paper, authors attempt to develop a mathematical model to calculate the air consumption and the tractive force according to Tex count of the weft yarn. The air consumption the actual tractive force were experimentally obtained compared to show the effectiveness of the model. This model could be further used to optimize the air consumption for a given yarn type and yarn count so that trial and error setting up and the material waste in the present practice could be eliminated while ensuring the minimal running cost.

The remaining part of the paper is structured in the following manner. Section II describe the development of the mathematical model while methodology is covered in section III. Section IV is dedicated to results and discussion. Conclusion will be the final section and it comes under section V.

II. DEVELOPMENT OF MATHEMATICAL MODEL

The main nozzle propels the weft yarn through the shed while the sub-nozzles avoid sagging of weft yarn on the path of weft insertion and also supports the weft movement. So the frictional force between the air and yarn is responsible for the weft yarn movement exerted by main and sub nozzles.

The total drag force constitutes of two components skin frictional force, equal to the integral of all shear stresses taken over the surface of the body and of pressure drag, integral of normal forces. Due to relative velocity between the yarn and the air stream a propulsive force which is proportional to the square of the relative velocity between the air stream and yarn is developed in the main nozzle and it is used to insert weft yarn in air jet weaving. The propulsive force is given by equation (1)

$$F = \frac{1}{2} C_d \rho \pi d l (V_a - V_y)^2 \qquad (1)$$

where F $, C_d, V_a, V_y$, ρ, l and d, are the longitudinal drag force along yarn axis, the air drag coefficient of weft yarn, the velocity of air along yarn axis, the velocity of yarn along its axis, the density of air, the yarn length subject to air and the diameter of the weft yarn respectively.

From the equation (1) it is evident that propulsion force increases with the increment of the air velocity and also with the weft yarn diameter. However, this equation is perfectly accurate under certain assumptions such as flow is steady state; yarn has negligible flexibility; there is a constant yarn velocity across the shed; there is no waste of air through the reed dents.

The Helix model equation was used to calculate the diameter of the weft yarn and it can be expressed as

$$d = 4.425 \times 10^{-3} \sqrt{T/\rho_f} \qquad (2)$$

where T and ρ_f are the Tex count of yarn and the fiber density respectively.

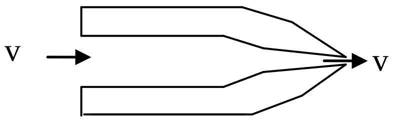


Fig.2: Cross section of a nozzle

Figure 2 shows a cross section of the main nozzle where there is a cross sectional reduction in flow path results in increasing the velocity of air flow and it practically increased to a supersonic flow. Only with mass conservation law, speed of air at the jet could not be determined due to compressible behaviour of the air and hence Bernoulli's equation should be used in conjunction with mass flow equations.

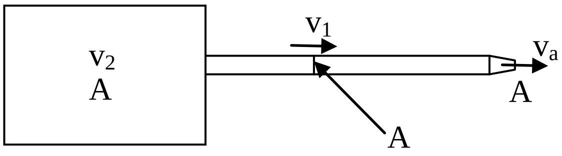


Fig.3: Pneumatic flow path to the nozzle

The cross sectional area of the compressed air tank (cross section 1), pneumatic horse connecting the air tank and nozzle (cross section 2), and nipple of the nozzle are A_2, A_1 and A_n respectively. The air velocities at the same cross sections are assumed to be v_2, v_1 and v_a respectively. Applying mass conservative law between cross section 2 and the nozzle outlet resulting in

$$\rho_1 v_1 A_1 = \rho_a v_a A_n \qquad \text{---------------}(3)$$

Applying Bernoulli's equation's compressible form across air tank and cross section yields the discharge velocity of the large reservoir as

$$v_1 = \sqrt{\frac{2\gamma}{\gamma-1}\frac{p_1}{\rho_1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\gamma-1/\gamma}\right]} \qquad \text{------------}(4)$$

Where ρ_1 p_1 and p_2 are the density of air at atmospheric pressure, atmospheric pressure and pressure of compressed air in the air tank respectively. The value of γ is equal to 1.4 for the air and it is a thermodynamic constant.

As the velocity of air at the nozzle is raised to supersonic level, Bernoulli's equation with Mach number, M is governing the equation for the air velocity at the nozzle outlet and considering the conservative nature of potential and kinetic energy at cross section 1 and nozzle outlet establishes the following relationship.

$$\frac{v_1^2}{2} + \frac{\gamma}{\gamma-1}\frac{p_1}{\rho_1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\gamma-1/\gamma}\right] = \frac{v_a^2}{2} + \gamma p_2 M^2 \qquad \text{------}(5)$$

Combining the isentropic relationship for air under the assumption that no shock waves are developed within the nozzle, the pressure of the compressed air and Mach number relationship can be stated as

$$\frac{p_2}{p_1} = 1 + \frac{\gamma}{\gamma-1}(M^2 - 1) \qquad \text{----------}(6)$$

Equation (4), (5), and (6) establish an expression for v_a as

$$v_a = \sqrt{\frac{4\gamma}{\gamma-1}\frac{p_1}{\rho_1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\gamma-1/\gamma}\right] + 2\gamma p_2 + 2p_2(\gamma - 1)\left(\frac{p_2}{p_1} - 1\right)} \qquad \text{-------}(7)$$

Having known the compression ratio and pressure of the compressed air, air velocity at the nozzle outlet can be calculated from equation (7) taking $\gamma = 1.4$ and density of air at 300C under atmospheric pressure $\rho_1 = 1.1644\ kgm^{-3}$.

Substitute for yarn diameter from equation (2) in (1) establishes an expression for the drag force F as given in equation (8) in terms of the air drag coefficient of weft yarn, relative velocity between air and the weft yarn, the yarn length subject to air, the density of air, the fiber density and Tex count of the yarn. However, the air drag coefficient is depend on the type of yarn.

$$F = 6.951 \times 10^{-3} C_d \, \rho l (V_a - V_y)^2 \sqrt{T/\rho_f} \text{ -----(8)}$$

III. METHODOLOGY

The Venturi tube was instrumented to measure the air flow rate through main air supply tube to air jet weaving machine due to unavailability of suitably accurate flow meter. The air flow rate Q is given by

$$Q = \sqrt{\frac{2\gamma RT(P_1 - P_2)A_1^2 A_2^2}{(\gamma - 1)(P_2 A_1^2 - P_1 A_2^2)}} \text{ --------(9)}$$

where P1, P2, R, T, γ, A1 and A2 are the pressure of air at tube 1 connected to constricted cross section, the pressure of air at tube 2 connected to large cross section, the density of air at tube 1, the density of air at tube 2, the universal gas constant, the absolute temperature, the ratio of specific heats of air, the area of the constricted cross section and the area of the larger cross section respectively.

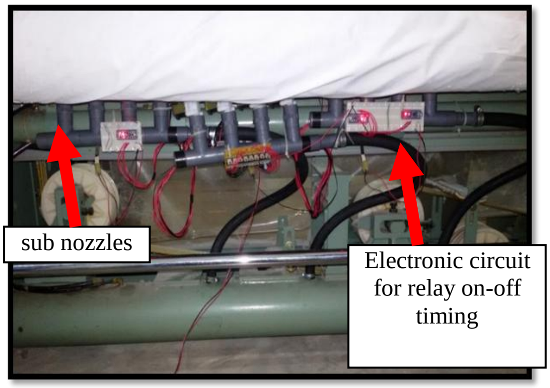


Fig. 4: Experimental setup

The testing was carried out on a Tsudakoma ZA 200 type air jet loomwith 16 sub nozzles arranged in four groupsas shown in Fig. 4. An arduino Mega board was used to switching the double solenoid pneumatic valves by sensing the position of the main shaft using a shaft encoder. This was instrumental to experiment in optimizing the air consumption of the air jet loom. Since the control circuits and its algorithm do not come under the purview of this paper, authors exclude it from this article.

Force exerted on the weft yarn was measured with a yarn tension meter, using a yarn tension meter a with the following specifications.

Manufacturer: MEMMINGER – IRO GMBH
Model: MLT WESCO D- 72277 DORNSTTEN
Range: 0 – 50 CN

The adjusted compressed air pressure P_2 for different yarn counts to achieve good quality fabrics (set value on trial and error) is measured using with pressure meter. The compressed air consumption was calculated with the following equation as given on the operational manual [23].

$$Q_{air} = rpm * w * k \text{----------(10)}$$

where is the reed with and is a factor specified in table 1 for different yarns and counts.

Yarn	Yarn count	k
OE cotton	Ne 5- Ne 10	0.045-0.055
OE cotton	Ne 10 - Ne 30	0.040-0.050
Carded cotton	Ne 12 - Ne 30	0.035-0.044
Worsted cotton	Ne 30 - Ne 50	0.030-0.04
Synthetic filament fibres	Den 30 - Den 400	0.045-0.055
Artificial fibres	Den 30 - Den 400	0.036-0.043
Highly twisted yarns	Den 70 - Den 300	0.055-0.058

Table 1: Optimal values of factor k [23]

From equation (7) velocity of air was calculated. The experimental speeds of the yarn V_y were obtained from the videos recorded by a high-speed camera of type Kodak Ekta Pro EM of which image capture rate was adjusted to 3000 frames per second. With that it was possible to obtain the position between two frames approximately to 0.2cm accuracy at the loom speed of 550 rpm. From the literature, the air drag coefficient of weft yarn were obtained. Theoretical air drag force or theoretical tractive force is calculated by equation (8). By comparing these values, the accuracy of the derived model was verified.

Using the average experimental pressure values substituted in equation (9), experimental air flow rate was experimentally obtained. The model determined air velocity at the outlet of the nozzle according to equation (7) was multiplied by the cross sectional area of the nozzle outlet to determine the theoretical air consumption of the air jet loom.

IV. RESULTS AND DISCUSSIONS

Air pressure was recorded with digital pressure sensor with an accuracy of two decimal places in psi units. Theoretical drag force was calculated using equation (7) while experimental tractive force was measured using yarn tension meter with one decimal place accuracy in cN. These values were given in table 2.

Table 2: Theoretical and experimental tractive force

Yarn Type	Yarn count (Tex)	Air pressure (Nm^{-2})	C_d X10^{-4}	Experimental drag force F(N)	Theoretical drag force F(N)
Cotton	20	289000	4.07	0.188	0.2161
Cotton	15	318000	3.97	0.181	0.2009
Polyester	20	314000	3.31	0.182	0.2017

It was observed that experimental and theoretical drag forces in close proximity and it is a promising evidence for the accuracy of the derived model.

Table 3: Pressure values at two ports of venturi tube for different yarn counts

Type of yarn	P1×105 (N/m^2)	P2×105 (N/m^2)	Main tank Pressure (N/m^2)
Cotton 20 Tex	6.79	6.565	2.5×105
Cotton 15 Tex	6.784	6.521	3.0×105
Polyester 20 Tex	6.313	5.942	4.0X105

The air pressure at two ports of the venturi tube were measured with digital pressure gauge and recorded in Table 3 for three types of different yarn count or yarn type. Substituting the pressure values given in table 3 in equation (9) the experimental air consumption was determined and tabulated in column 3 in Table 4. The nozzle air velocity multiplied by the cross sectional area of the outlet of the nozzle yields the theoretical air consumption given in column 2 in Table 4. When comparing the theoretical air consumption calculated by the derived model was much in consistent with that of experimental value. This also endorsed the validity of the derived model.

Table 4: Theoretical and experimental air consumption

Type of yarn	Theoretical (m^3/s)	Experimental (m^3/s)
Cotton 20 Tex	0.3253	0.3552
Cotton 15 Tex	0.3803	0.3842
Polyester 20 Tex	0.4964	0.4731

It was also observed that the compressed air consumption is increased with the increment of weft insertion speed or loom speed though the experimental results were obtained at a constant 550 rpm loom speed. From the readings summarized in Table 3 and 4, provided evidences in favour of different traction force as well as different air consumption for a good quality weave for different yarn types due to the yarn surface properties. With the increment of Tex count, the traction force is increased and hence the required pressure for a quality weave decreases, and so as the air consumption.

V. CONCLUSION

A mathematical model has been developed to calculate the air consumption and the tractive force according to Tex count of the weft yarn. Using a venturi tube, experimental air consumption was obtained while the actual tractive force was experimentally obtained with a digital tension meter. The close comparability and consistence of the experimental and theoretical values endorsed the accuracy of the model developed. Further, in the discussion, a theoretical explanation was given for the different air consumption and the different tractive forces. This model can be extended to optimize the air consumption for a given type of weft yarn so that the trial and error method to set the air jet pressure can be avoided owing to which a considerable waste in setting up the machine can be saved. Ultimately efficiency of the weaving would be improved due to optimal settings.

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