Journal of Environmental Science and Engineering B 5 (2016) 26-34
doi:10.17265/2162-5263/2016.01.004

# Increasing the Energy Efficiency of Air Jet Weaving Based on a Novel Method to Exploit Energy Savings Potentials in Production Processes of the Textile Industry

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**Abstract:** This article deals with the energy efficiency of textile weaving machines. A method based on exergy balances has been developed at the Institute for Textile Technology RWTH Aachen University (ITA), Aachen, Germany in order to improve energy efficiency textile machines. The relay nozzles of the air-jet weaving technology need up to 80% of the energy of the weaving machine. At ITA, a new nozzle concept was developed. The developed geometry is a so called High-Volume-Low-Pressure nozzle (HVLP nozzle), based on convergent nozzle aerodynamic theory. With this concept, energy savings up to 30% are possible.

**Key words:** Energy efficiency, air jet weaving, relay nozzle, energy consumption.

## 1. Introduction

The textile industry is an energy intensive industry. Increasing energy costs is a challenge for textile manufacturers as well as for the developers of textile production machines. For example, air-jet weaving is the most productive but also most energy consuming weaving method [1]. Air-jet weaving is a type of technology in which the warp is inserted into the warp shed with compressed air by different nozzles types. In Fig. 1, a schematic view of the weft insertion components is shown. Current state of the art air-jet weaving machines employ a tandem and main nozzle combination at the purpose to provide the initial acceleration to the weft yarn, and a series of relay nozzles to keep constant yarn velocity of about 55-80 m/s across the weave shed during the weft yarn insertion-process.

A profiled reed provides guidance for the air. At the end of the insertion process, a nozzles catches and stretches the yarn at the right side of the machine. A cutter is used to cut the yarn when the insertion is completed and the beat-up movement complete the fabric production process [2].

The air-jet weaving machine combines high performance (Table 1) with low manufacturing requirements, because differently from rapier and projectile machines, the filling medium is just air and no mechanical parts are directly involved in the weft insertion process. It has an extremely high production rate up to 1,100 weft insertions per minute and it covers a wide range of processing yarns like spun and continuous filament yarns. However, the main drawback regarding of the technology is the very high energy consumption (Table 1) due to the compressed air usage which is required during the weft insertion process. Since the cost of energy has a systematic increasing trend, power consumption is still a challenging issue. In particular, it is the limiting factor for such technology in the countries, where energy costs represents a large share of the manufacturing

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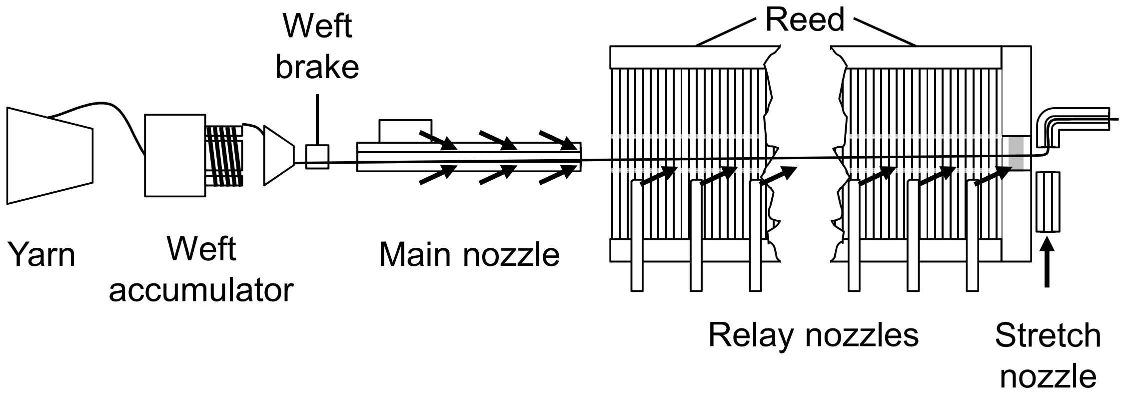



**Fig. 1 Schematic view of air-jet weft insertion system [2].**

**Table 1 General characteristics of airjet weaving machine [2, 3].**

| Air jet weaving machine | |
|---|---|
| Weft insertion rate | 2,000 m/min |
| Average specific energy consumption (kWh/kg of woven fabric) | 3-5 |

costs. An overview of the manufacturing cost of a woven fabric can be seen in Table 2.

For instance, in Italy, the total manufacturing cost is 0.579 USD/m of woven fabric and power cost corresponds to 27% (0.156 USD/m). In other countries, such as India or China, the total manufacturing costs are less, 0.265 USD/m and 0.215 USD/m respectively, but on the other hand, the power consumption are responsible for 35% (0.093 USD/m) and 38% (0.083 USD/m) of the entire value respectively. In order to decrease the energy consumption and increase the energy efficiency, air-jet weaving machines are under constantly development. At the Institute for Textile Technology RWTH Aachen University (ITA), Aachen, Germany, a novel method based on exergy balances has been applied at the purpose of reducing the power costs while keeping constant fabric quality. The study focused on the air flow field of the relay nozzles and on the interaction with the profiled reed. A detailed picture of the position of the relay nozzles and the profiled reed is shown in Fig. 2.

Finally, the result of the research led to the development of a new geometry of the relay nozzle which is able to provide the same value of propulsive force to the weft yarn at a lower operating pressure level. This new concept of relay nozzle is able to work at 1-2 bar inlet overpressure in place of 5 bar, as it happens for current relay nozzles available on the market [4]. In such a way, the productivity is kept constant and the costs associated to the compressors to pump up the air decreased.

**Table 2 Overview of the manufacturing costs of a woven fabric [5].**

| | Brazil | China | Egypt | India | Italy | Korea | Turkey | USA |
|---|---|---|---|---|---|---|---|---|
| Waste | 0.005 | 0.004 | 0.006 | 0.004 | 0.007 | 0.004 | 0.006 | 0.006 |
| Labour | 0.025 | 0.012 | 0.01 | 0.013 | 0.206 | 0.082 | 0.074 | 0.13 |
| Power | 0.075 | 0.083 | 0.035 | 0.093 | 0.156 | 0.051 | 0.091 | 0.052 |
| Auxiliary material | 0.028 | 0.036 | 0.05 | 0.062 | 0.08 | 0.047 | 0.051 | 0.033 |
| Depreciation | 0.063 | 0.062 | 0.056 | 0.067 | 0.089 | 0.059 | 0.064 | 0.095 |
| Interest | 0.04 | 0.018 | 0.029 | 0.026 | 0.041 | 0.019 | 0.021 | 0.029 |
| Total manufacturing costs (USD per meter of fabric) | 0.236 | 0.215 | 0.186 | 0.265 | 0.579 | 0.262 | 0.307 | 0.345 |

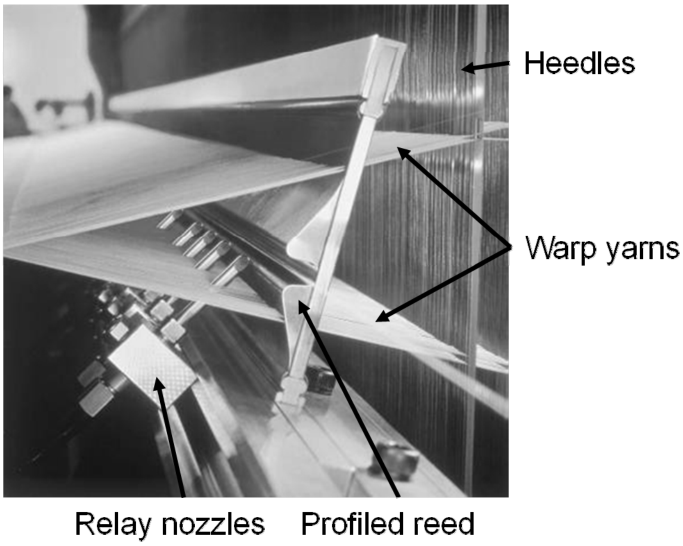



**Fig. 2 Detailed view of the relay nozzle and the profiled reed.**

## 2. Meterial and Methods

*2.1 Methods*

Increasing the energy efficiency of a production machine is one of the biggest challenges for the machine producer. Therefore, an approach was developed at ITA especially for textile machines. The 6ζ method developed at ITA [4] provides a framework that allows for the systematic analysis of production machines in order to:

- detect and quantify energy efficiency potentials in production processes of the textile industry in a consistent way;
- derive actions to exploit the identified potentials in an economically feasible way.

The method provides an overview related to energy efficiency improvements in industrial environments. Nevertheless, this method needs extensions in order to be consistent and universally applicable. Therefore, it has been integrated with three basic pillars:

(1) consistent assessment of energetic inefficiencies by means of exergy balances;

(2) clear focus on economic measures;

(3) tool for the systematic derivation of actions for energy efficiency improvements.

These pillars are integrated into the established 6ζ method. By considering the symbol for the exergetic efficiency ζ (zeta) and the six consecutive steps, the extended method is considered as 6ζ method [4]. Fig. 3 shows the structure of the 6ζ method.

Pillar 1: Exergy balances:

The use of exergy balances is fundamental for assessing the energy efficiency of arbitrary production processes. Exergy balances are of particular value if the considered process consumes energy forms that are not fully convertible such as heat, steam or compressed air.

Pillar 2: Focus on economic measures:

The 6ζ method has a clear focus on economic measures that support entrepreneurial decisions. In the analysis phase, subsystems are prioritised according to costs due to energetic in efficiencies instead of applying pure physical measures. The Net Present Value (NPV) method in combination with scenario techniques ensures a rational economic performance evaluation of generated improvement measures.

Pillar 3: Novel tool for the derivation of actions for energy efficiency improvements:

The 6ζ method comprises a two-step scheme for the development of energy efficiency improvement measures. Firstly, machine components of the target machine categorised in two dimensions. The first

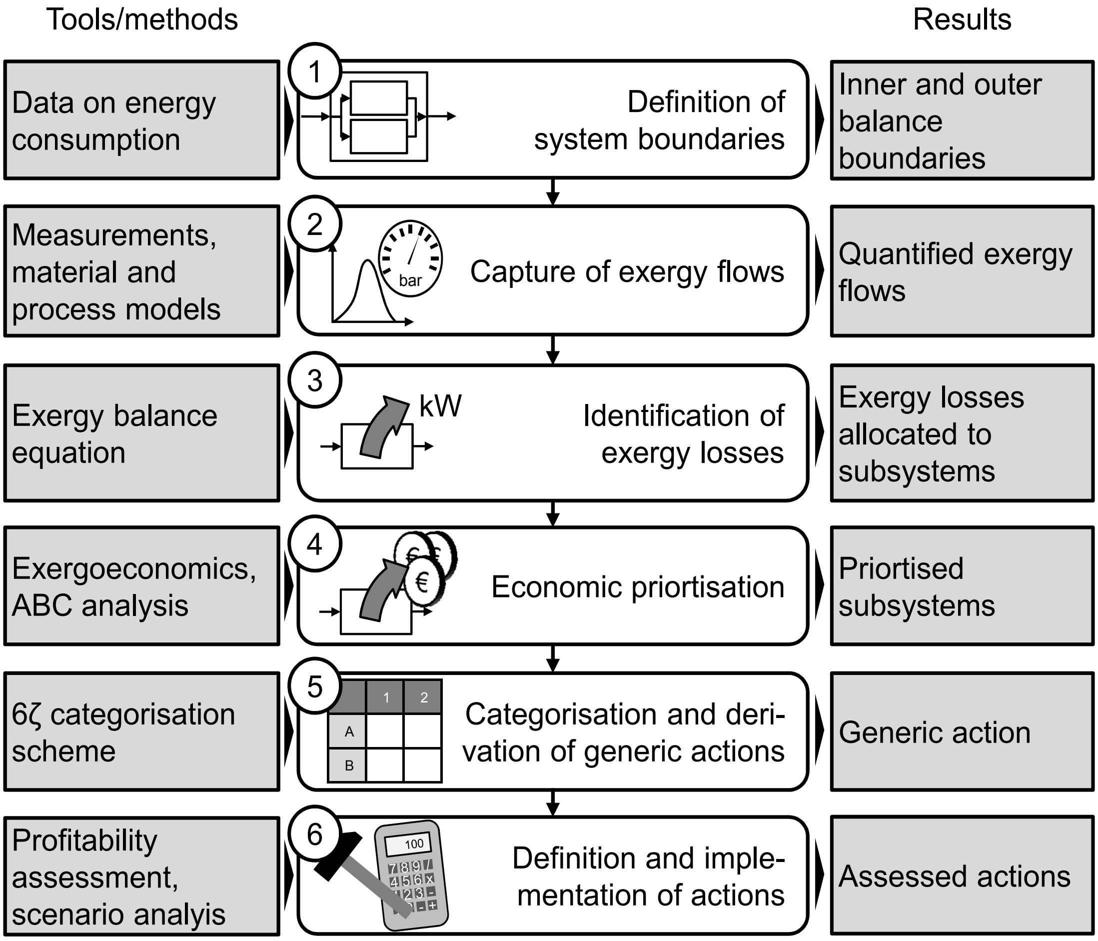
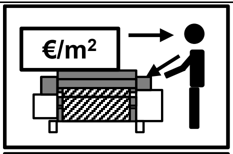
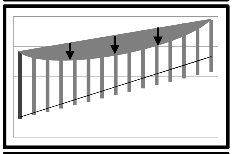
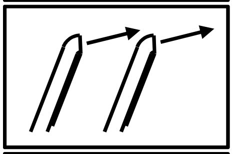
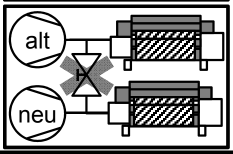



**Fig. 3 Structure of the 6ζ method [5].**

dimension distinguishes the components according their contribution to value creation. The latter distinguishes whether dissipation is an incorporated attribute of the working principle (e.g. driving a yarn by air friction) or not (e.g. movement of a rapier). The second step provides generic improvement measures depending on the categorization result. This scheme provides an added value to the user since improvement measures are generated in an efficient as well as effective way. Exergy-based system analysis was found to be the basis for the consistent assessment of energy efficiency in production processes. Furthermore, rational economic performance evaluation is fundamental in the case of energy efficiency improvements. Examples show that the implementation of profitable energy efficiency measures often lags due to long payback periods. The 6ζ method consistently applies the net present value method in combination with scenario techniques in order to assure rationality. In general, the 6ζ method focuses on monetary measures. In addition, there is a lack of systematic support in the development of energy efficiency improvement measures. A novel evaluation scheme helps to close this gap. As a result, users' knowledge comes into consideration if and only if there are user-dependent saving potentials. The method has been applied successfully to the air-jet weaving technology (Table 3) and exgery based system analysis leads to in the identification of efficiency potentials that are hidden to conventional approaches. The added value from exergy based analysis justifies the more complex theory behind it.

**Table 3 Energy efficiency measures for the analyzed processes.**

| Air-jet weaving | | |
|---|---|---|
|  | Visualisation of energy costs | Economic potential, high technology readiness |
|  | Improved relay nozzle settings (including tool) | Economic potential, high technology readiness |
|  | Novel relay nozzle concept | Economic potential, low technology readiness |
|  | Several compressed air grids | Moderate economic potential, medium technology readiness |

### *2.2 Application of the Methods*

In air-jet weaving, the largest share of energy consumption can be allocated to the pneumatic components. The relay nozzles as well as their valves cause the major share of energetic inefficiencies within the pneumatic system. Therefore, a new nozzle geometry concept has been developed. This concept makes it possible to operate the manufacturing process in a subsonic range.

The developed geometry is a so called High-Volume-Low-Pressure nozzle (HVLP nozzle), based on convergent nozzle aerodynamic theory. Characteristic of this nozzle is the relatively large internal diameter up to 5 mm, which makes it possible to work with larger volume flows at a lower operating pressure. Current 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 [2]. The movement of the yarn is a complex motion and it depends on the outer flow field of the relay nozzles.

Therefore, the main parameter which characterizes a relay nozzle is the value of thrust which it is able to provide to the filling yarn. The total force on a characteristic yarn length placed in a stream of fluid consists of skin friction, equal to the integral of all shear stresses taken over the surface of the body and of pressure drag, integral of normal forces. The sum of the two is called total or profile drag. The component of the resultant force parallel to the in disturbed initial velocity is referred to as the friction force $F_f$, and the component perpendicular to that direction is called drag force $F_d$, as shown in the Fig. 4.

The propulsive force to move the yarn in the air-jet insertion is provided by the friction between the air and the yarn surface and is given by Eq. (1):

$$F_f = \frac{1}{2} C_f \rho (U - V)^2 \pi D L \qquad (1)$$

Where,

$C_f$ = skin friction coefficient;

$\rho$ = air density;

$U$ = air velocity;

$V$ = yarn velocity;

D = yarn diameter;

L = yarn length subject to air, yarn characteristic length.

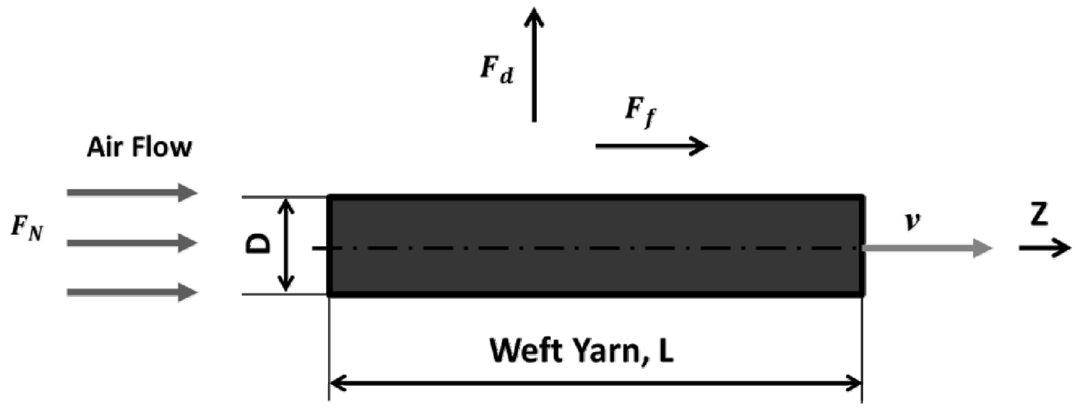



**Fig. 4 Theoretical model of the forces acting on the weft yarn.**

This force is proportional to the square of the relative velocity between the air stream and yarn. The propelling force increases with grow of the air velocity and the weft yarn diameter.

Assuming the further hypothesis:

- steady state flow;
- negligible yarn flexibility;
- air flow coming from relay nozzles aligned with yarn motion;
- constant yarn velocity across the shed;
- no waste of air through the reed dents.

A reasonable theoretical model can be drawn to point out the forces involved in the nature of the weft insertion process.

The thrust, $F_N$, provided by the relay nozzle to the yarn is the key parameter for the productivity of the machine and for the quality of the product. To rise this value would mean to increase the friction force which is actually the propelling force acting on the yarn and responsible of the fabric production rate.

The research carried out at ITA made real an innovative relay nozzle concept which is able to drive the weft yarn by using only a 1 bar overpressure in place of 5 bar as commonly applied in current air-jet technology. The use of 5 bar in inlet pressure does not increase the outer flow velocity of the convergent nozzles, but only the mass flow rate. By employing the new relay nozzle concept, the costs associated to the compressors are strongly reduced, but machine productivity and product quality are held constant. The model drawn in Fig. 5 is a reasonable first approximation and it gives an insight to understand the physics of the process even if it does not take into account the flow interaction with the profiled reed. In the real cases, a large amount of air coming out of the relay nozzles, more than 50%, is wasted though the dents of the reed. Consequently, deep aerodynamic simulations have been carried out in order to validate the theoretical model and provide a more faithful representation of the flow field produced by the relay nozzles.

## 3. Results

For the validation of the theoretical model, different flow simulations have been made. The simulations are done with the Computational Fluid Dynamics (CFD) simulation tool ANSYS Fluent from ANSYS, Inc., Canonsburg, USA. Within the simulation, the free flow field of the nozzle was simulated. The simulation is based on the following assumptions:

- compressible flow field;
- ideal gas;
- steady state flow.

With these assumptions, a CFD model was set up and a CAD-model of the new nozzle concept was integrated into this model. Behind the nozzle outlet is a free flow field with ambient pressure. At the inlet of the nozzle, 1 bar overpressure was set as condition. The CFD model with the simulated flow field is shown in Fig. 5.

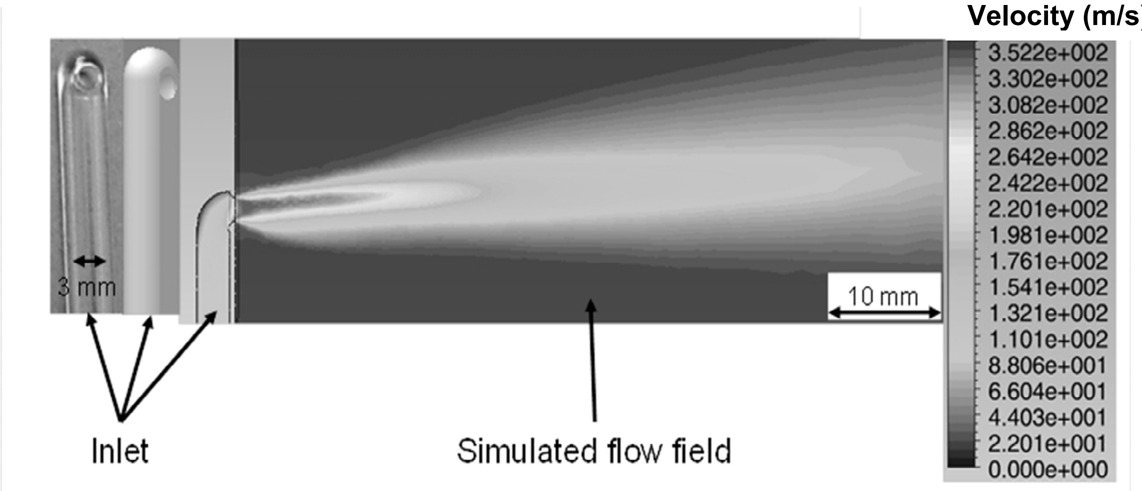



**Fig. 5 Simulated flow field of the new nozzle concept.**

The air stream out of the nozzle is very compact (e.g. low divergence flow, no shock waves) and has a small about 6-8 degree blowing angle. In agreement with the convergent nozzle theory, it can be drawn from the simulation that sonic conditions are achieved at the outlet surface (M = 1 and v = 350 m/s). The nozzle is in chocking condition and the mass flow rate reaches the highest possible value that the outer surface can allowed by taking into account the initial boundary conditions of pressure and temperature. Moreover, the expansion of the flow occurs outside of the nozzle by means of dumped oscillations. In Fig. 6, the velocity of the air stream up to a distance of 130 mm behind the nozzle is shown. It shows that on the vertical axes the velocity of the air and on the horizontal axes, the distance downstream the nozzle. The nozzle is located in the origin. It can be clearly seen where the acceleration region of the yarn is located, exactly where air velocity is higher than yarn speed range. It can be drawn that the velocity is over the critical velocity of 65 m/s up to a distance of around 80 mm behind the nozzle. Moreover, assuming an average yarn velocity of 65 m/s, the air will accelerate the yarn up to 80 mm downstream the relay nozzle where the following nozzle will be in turn start to operate.

## 4. Discussion

The simulation of the new relay nozzle concept shows potential for using this nozzle within the weaving process [6]. With the new nozzle, it is possible to have an acceleration region of the yarn over a distance up to 80 mm downstream the nozzle. The distance between the relay nozzles of a weaving machine is between 70 mm and 75 mm depending on the machine and the produced material [7]. Therefore, the simulation justifies the nozzles spacing value along the shed. The simulation shows the free flow field of the new nozzle concept and therefore, potential to use the nozzles in a weaving process. Within the weaving process, the reed has a relevant influence on the flow field. This influence is not considered within the simulation. During the weft insertion process, the reed act like a guiding channel for the air and at the same time, a huge amount of compressed air is dispersed through the dents of the reed itself. Eventually, by using the new relay nozzles at 1 bar operating pressure in place of 3-5 bar like in the state of the art, the use of smaller compressors is enabled and a relevant reduction of the energy consumption of the weaving machine is achieved. In Table 4, the energy consumption of compressor depending on the operating pressure is shown.

It can be drawn that the use of a reduced operating pressure leads to an energy reduction up to 30%. In the case of 5 bar operating pressure, the compressor has an energy consumption of 5.35 kW/m³/h. If the

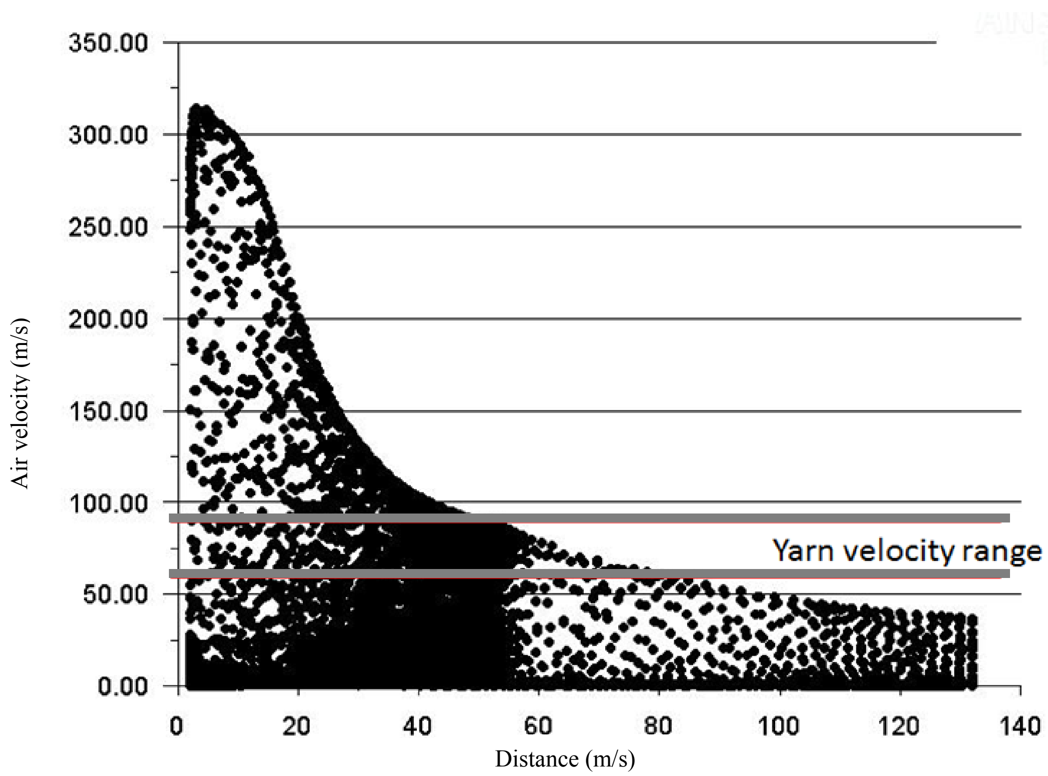



**Fig. 6 Velocity of the air stream downstream of the nozzle outlet.**

**Table 4 Energy consumption of a compressor depending on the operating pressure.**

| Operation pressure (bar) | Energy consumption (kW/m³/h) |
|---|---|
| 1 | 2.8 |
| 1.5 | 3.3 |
| 2 | 3.56 |
| 2.5 | 3.84 |
| 3 | 4.12 |
| 3.5 | 4.41 |
| 4 | 4.72 |
| 4.5 | 5.04 |
| 5 | 5.35 |
| 5.5 | 5.42 |
| 6 | 5.5 |

operation pressure reduced to 1 bar, the energy consumption is 2.8 kW/m³/h.

## 5. Conclusion

At the Institute for Textile Technology RWTH Aachen University, Aachen, Germany, a novel method has been developed to identify potentials in saving energy of textile production processes [5, 8]. The air-jet weaving process is the most productive but also the most energy intensive weaving process. With the 6ζ method, the pneumatic components of the machine were identified as biggest energy consumer. Based on a theoretical model of the weft insertion, a new concept for the relay nozzle has been drawn. The new nozzle is able to reach sonic condition at the outlet surface by employing a 1 bar inlet overpressure in place of 5 bar, as commonly used in the state of the art machines. Moreover, even by reducing the inlet pressure, the mass flow rate does not decrease thanks to the higher nozzle internal diameter up to 5 mm. Consequently, the nozzle thrust is not negatively affected or reduced and the machine performance holds constant. By means of CFD simulations, the potential of the nozzle is shown and an energy reduction up to 30% is possible. Nevertheless, the simulation includes a faithful reproduction of the free flow field of the relay nozzle, without taking into account the interaction with the profiled reed, and therefore, it gives a first insight on how to reduce the power consumption of the weft insertion process. The next step is the validation of the new nozzle concept within the weaving process. Furthermore, the next studies should also include the interaction between the relay nozzle and the reed in the weaving process at the purpose of reducing the amount of wasted air through the dents of the reed.

## Acknowledgement

The European Commission gratefully acknowledged for its support of the Marie Curie program through ITN EMVeM project, Grant Agreement No: 315967.

Project VIP0477 in form of assistance "Validation of the Potential Innovation in the Scientific Research" supported by the Federal Ministry for Education and Research.

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