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Energy Efficiency Approach to Reduce Costs of Ownership of Air Jet Weaving

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Abstract**—**Air jet weaving is the most productive, but also the most energy consuming weaving method. Increasing energy costs and environmental impact are constantly a challenge for the manufacturers of weaving machines. Current technological developments concern with low energy costs, low environmental impact, high productivity, and constant product quality. The high degree of energy consumption of the method can be ascribed to the high need of compressed air. An energy efficiency method is applied to the air jet weaving technology. Such method identifies and classifies the main relevant energy consumers and processes from the exergy point of view and it leads to the identification of energy efficiency potentials during the weft insertion process. Starting from the design phase, energy efficiency is considered as the central requirement to be satisfied. The initial phase of the method consists of an analysis of the state of the art of the main weft insertion components in order to point out a prioritization of the high demanding energy components and processes. The identified major components are investigated to reduce the high demand of energy of the weft insertion process. During the interaction of the flow field coming from the relay nozzles within the profiled reed, only a minor part of the stream is really accelerating the weft yarn, hence resulting in large energy inefficiency. Different tools such as FEM analysis, CFD simulation models and experimental analysis are used in order to design a more energy efficient design of the involved components in the filling insertion. A different concept for the metal strip of the profiled reed is developed. The developed metal strip allows a reduction of the machine energy consumption. Based on a parametric and aerodynamic study, the designed reed transmits higher values of the flow power to the filling yarn. The innovative reed fulfills both the requirement of raising energy efficiency and the compliance with the weaving constraints.

Keywords**—**Air jet weaving, aerodynamic simulation, energy efficiency, experimental measurements, power costs, weft insertion.

I. Introduction

AIR jet weaving is a type of weaving in which the filling yarn is inserted into the warp shed with compressed air. Fig. 1 shows a schematic of air-jet weaving utilizing a multiple nozzle system and profiled reed which is the most common configuration in the market. Yarn is drawn from a filling supply package by the filling feeder, and each pick is measured for the filling insertion by means of a stopper. Upon release of the filing yarn by the stopper, the filling is fed into the reed tunnel via tandem and main nozzles. The tandem and main nozzle combination provides the initial acceleration to the filling yarn. Subsequently, the relay nozzles are turned on in order to keep high velocities of the flow field inside the weft acceleration region and in order to drive the yarn across the shed. Once the yarn arrives at the receiving side of the machine, the profiled reed which acts as a channel guide for the air flow pushes the weft to cloth fell, and the fabric is created [1]. A cutter is used to cut the yarn when the insertion is completed.

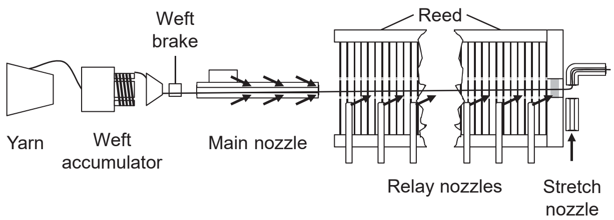

Fig. 1 Schematic view of air-jet weft insertion system

The air-jet weaving machine combines high performance (Table I) 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 [2]. It has an extremely high production rate up to 1100 weft insertions per minute and it covers a wide range of processing yarns like spun and continuous filament yarns.

TABLE I
General Characteristics of Air Jet Weaving Machines

Air Jet weaving machine	
Weft Insertion rate (m/min)	2000
Average Specific Energy consumption (kWh/kg of woven fabric)	10 – 12

Despite the very high production rate, the main drawback affecting negatively this technology is the very high energy consumption (Table I) due to compressed air demand which is required during the weft insertion process and due to massive waste of such compressed, lost in the space between the reed metal strips without giving a contribution to the weft insertion process. Since the cost of energy has a systematic increasing trend, power consumption is still the most challenging issue for the textile production machine manufacturers [2]. In particular, it is the limiting factor for such technology in the countries where energy costs represent a large share of the

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manufacturing costs [3]. An overview of the manufacturing cost of a woven fabric can be seen in Table II [4]. 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, respectively 0.265 USD/m and 0.215 USD/m; on the other hand, the power consumption is responsible respectively for 35% (0.093 USD/m) and 38% (0.083 USD/m) of the entire value.

TABLE II
MANUFACTURING COSTS OF A WOVEN FABRIC [4]

	Brazil	China	India	Italy	Turkey	USA
Waste	0.005	0.004	0.004	0.007	0.006	0.006
Labour	0.025	0.012	0.013	0.206	0.074	0.130
Power	0.075	0.083	0.093	0.156	0.091	0.052
Auxiliary material	0.028	0.036	0.062	0.080	0.051	0.033
Depreciation	0.063	0.062	0.067	0.089	0.064	0.095
Interest	0.040	0.018	0.026	0.041	0.021	0.029
Total costs	0.236	0.215	0.265	0.579	0.307	0.345

In order to provide a general overview on the achievements made in reducing the energy consumption of air jet weaving, a complete study on the state of the art is conducted by taking into account the achievements both in the research world and in the industry sector (Table III). By taking into account the results coming from the complete analysis of the state of the art, it can be drawn that a fundamental region of the weft insertion passage is not yet properly investigated, therefore lacking of any possible improvements. Large margins of improvement are left in the design of a new reed geometry which can enable higher energy savings by optimizing the amount of air that remains inside the weft acceleration region. At the purpose of decreasing the power costs, a novel method based on energy efficiency as a central requirement in the design phase has been developed at the Institute for Textile Technology RWTH Aachen, Germany. Such method aims at increasing the energy efficiency of the machine by using an innovative concept of profiled reed. Characteristic of the newly designed reed is the more enclosed structure which prevents air from spreading to the outer parts and it fosters an increase of the mass flow rate, inside the shed, which is really participating to the propulsive force on the weft yarn.

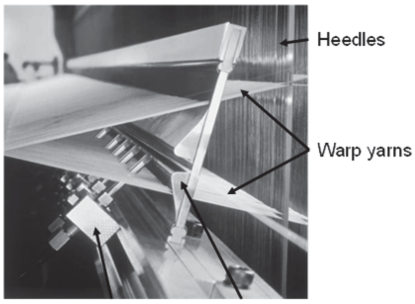

Fig. 2 Detailed view of the relay nozzle and the profiled reed

TABLE III
ANALYSIS OF THE STATE OF THE ART

What has been done so far in the field of reducing energy consumption of air jet weaving	
Research	Industry
Reduction of the blowing time of relay nozzles [6], [9], [10]	Calibration of relay nozzles
Development of High Volume Low Pressure relay nozzle [2], [6]-[8]	Reduction and control of the nozzles blowing time
Alternative ideas to reduce the wasted flow through the backwards of the profiled reed (use of a second reed, use of additional nozzles, increase the thickness of the metal strips) [10]	Use of different pressurised tanks for the main nozzle and for the relay nozzles and control of the arrival time of weft yarn
CFD simulations on single elements involved in the weft insertion process and experimental measurements investigation of the leakage through the reed dents [5]	Adjustments on the pressure values of the relay nozzles and main nozzles according to the employee experience and yarn material
Experimental measurements and simulations of air velocity distribution into a U-shaped weft passage profile [11]	Use of solenoid valve to regulate the air flow passage
Study on weft dynamics into a profiled reed [12]	Use of suction nozzle to reduce the consumption of mass flow rate
Experimental analysis of the air flow through the weft passage, by mounting different relay nozzles [13]	Usage of reeds with a shorter lower jaw in order to place the relay nozzles closer to the filling yarn

A detailed picture of the position of the relay nozzles and of the profiled is shown in Fig. 2. Finally, the result of the research leads to the investigation of the flow field throughout the shed and to the implementation of a new air tunnel shape, able to decrease the waste of air and the value of working pressure of the relay nozzles while keeping constant the productivity.

II. METHOD

Increasing the energy efficiency of a production machine is one of the biggest challenges for the machine producer. The introduction of aspects of energy assessment into the process for the design of industrial machineries extracts useful elements from the field of the design theory. Design for "X" (with "X" = strength, manufacturing, recycling, cost, etc.) is an important strategy especially in engineering design. Until now, very few structured approaches for machinery design that take the energy impact of the resources into account have been proposed in the field of design theory and methodologies and they have application limited to specific machine typology. Therefore, an approach was developed at ITA especially for the textile machines. Established design methodologies have not yet considered energy efficiency as a central requirement of technical systems. A systematic approach for the development of energy efficiency machine tools [14], provides general concepts that can be applied to other type of industrial machinery. Energy efficiency is taken as central property in the design process and represents a new requirement / property to be defined in the phase of design problem / task definition. In contradiction with established methodologies, the approach (Fig. 3) includes an initial analysis of existing technical systems and the individuation and classification of their prior and relevant energy consumers (sub-systems and processes). The identified major consumers are afterwards systematically addressed to reduce their energy consumption: interaction of the flow field coming from the relay nozzles within the profiled reed. A following step of analysis consists of the verification of the system design, evaluating the system behavior with several tools (e.g. FEM analysis, simulation models, experimental analyses, etc.). Currently, the design of a machine is basically defined on the meeting of objective requirements and performance (production output, dynamic and kinematic properties, etc.) at the minimum cost. The idea at the base of this contribution is to propose energy-efficiency as a new additional and central property in the design process of a machine tool supported by specific methodologies. It must be noted that in general, energetic efficiency depends on how a machine is made (“design”) and how it is used (“management”). These two aspects cannot be fully separated and a designer must take into account how the machine will be used. Since nowadays products become more and more multi-disciplinary by the constantly increasing integration of added functionality and product intelligence and since energy is a global design attribute which is influenced by all disciplines, the development of energy analysis methodologies, both numerical and experimental, is able to decrease the environmental impact and to keep constant the product quality requires an integrated research strategy.

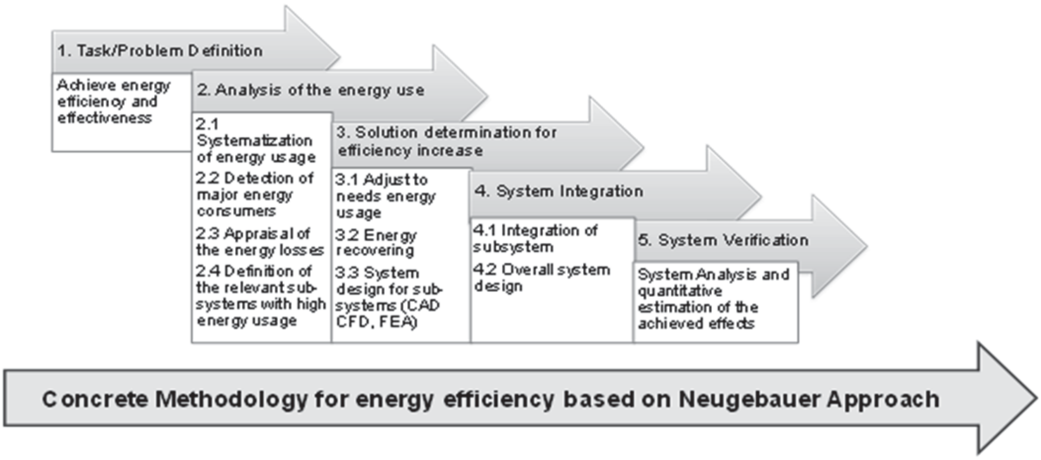

Fig. 3 Methodology for energy efficiency

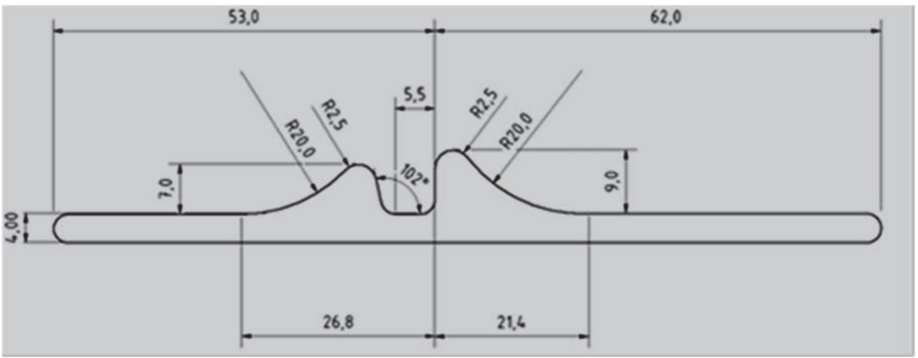

Fig. 4 Representation of a state if the art metal strip

III. Application of the Method

When the filling yarn is inserted through the shed, it lies relatively far from its final position. This is because of the acute angle of the shed opening. Therefore, the newly inserted filling yarn needs to be brought to its final position by pushing through the warp sheet. Beat-up is the process of pushing the last inserted filling yarn to the cloth fell by using the reed. The reed is a closed comb of flat metal strips (Fig. 4). These metal strips are evenly spaced at the intervals that correspond to the spacing of warp ends in the fabric.

Therefore, the reed is also used to control warp yarn density in the fabric and weight as a consequence. The spaces between the metal strips are called "dents". After beating up the filling, the reed is withdrawn to its original rest position before the insertion of the next pick (Fig. 5).

The shape and thickness of the metal wires used in the reed are important parameter for the fabric features. Reed manufacturing depends on several considerations including fabric appearance, fabric weight (ends per unit width), beat-up force, air space requirement and weave design. During the weft insertion, 80% of the air injected by the relay nozzles leaks throughout the reed, whereas only 20% of air actually drives the yarn (Fig. 6). On industrial scale, such inefficiency mirrors into a relevant increase of the total cost of ownership of the machine.

The theoretical model (Fig. 7) shows a snapshot of weft insertion process and it represents the starting point for the investigation of the flow field along the reed channel.

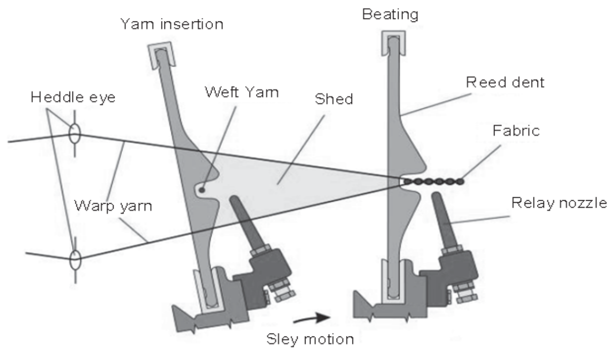

Fig. 5 Schematics of beat up motion

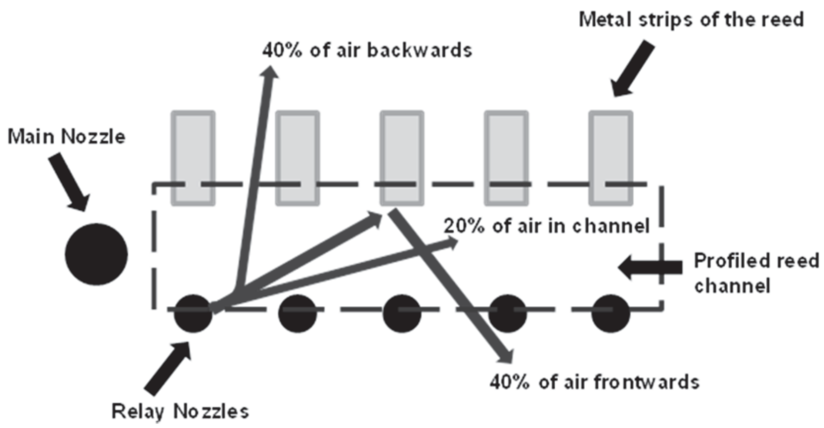

Fig. 6 Schematic of weft passage region

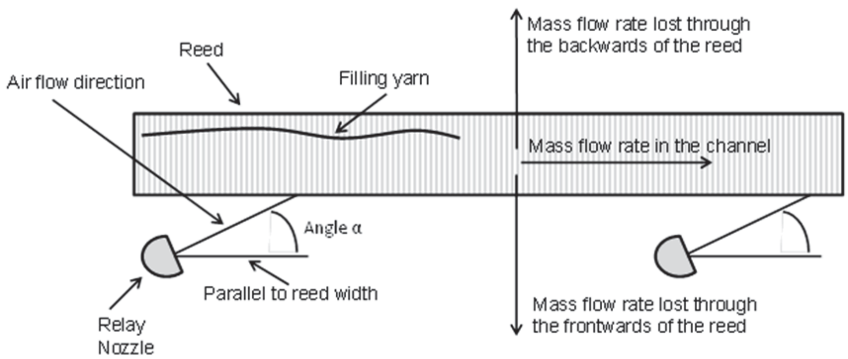

Fig. 7 Theoretical model of the weft insertion in air jet weaving

The driving force which moves the yarn in the reed channel is provided by the friction in (1) between the air and the yarn surface

$$F_f = \frac{1}{2}\,\pi\, D\, \rho \int_{yarn} C_f (U-V)^2\, dx = \frac{d(M\,V)}{dt} \quad (1)$$

with; C_f = skin friction coefficient, ρ = air density, U = air velocity, V = yarn velocity, D = yarn diameter, x = yarn length subject to air flow within the reed, M = wet mass of 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 the air velocity and it depends on the amount of mass flow rate coming out from the relay nozzles too. To increase the value of mass flow rate inside the reed channel would mean to increase the friction with the filling yarn and hence the productivity of the machine in terms of picks per minute. In the other words, it would be possible to keep constant the propulsive force to the weft yarn at a lower inlet pressure. In order to validate the theoretical model and to provide a more faithful representation of the flow behaviour along the shed, computational fluid dynamic (CFD) simulations and experimental measurements are carried out.

IV. Results

In order to study the energetic behaviour of flow field along the weft passage region, CFD simulations are carried out. The simulations are conducted with the simulation tool ANSYS Fluent from ANSYS, Inc., Canonsburg, USA. The assumptions of compressible ideal gas and steady state flow are taken into account. With these assumptions, a CFD model was set up, and a CAD-model was integrated into this model. The interaction of the flow field with the reed dents is simulated, and the main energy losses are visualised and analysed along the shed (Fig. 8). Downstream of nozzles is a free flow field with ambient pressure.

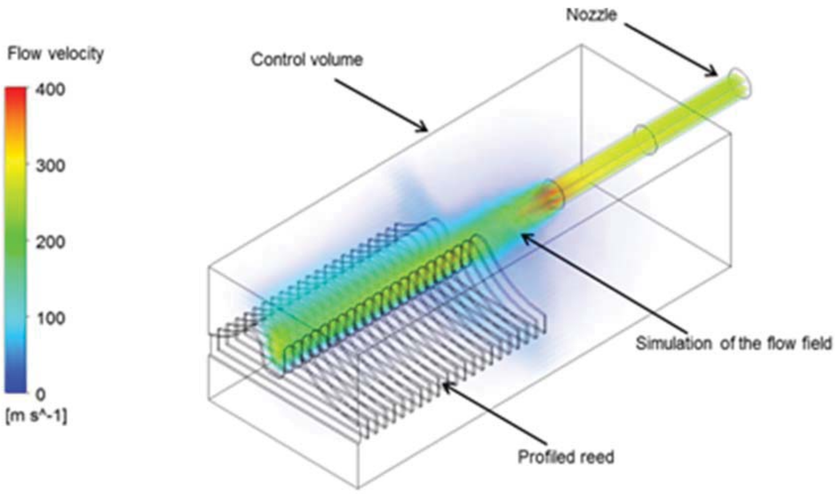

Fig. 8 Flow field simulation model along the air tunnel

The air stream tends to escape from the weft acceleration region towards the forward open side of the reed and through the back. It can be drawn that the walls of the metal strips behave as a suction sink for the flow field which is forced to vanish through the dents of the reed (Fig. 9).

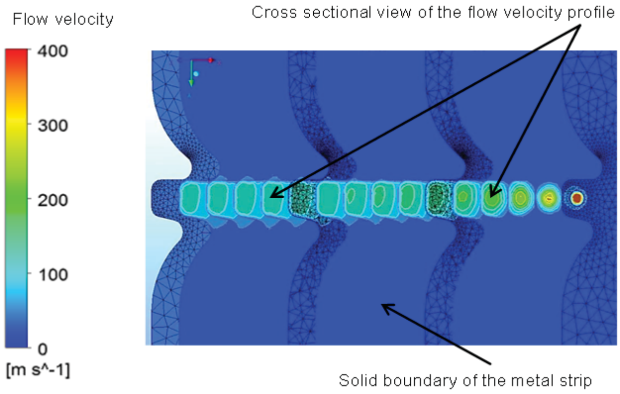

Fig. 9 View in detail of CFD simulation at the boundary walls

Consequently, such amount of air is wasted and no longer able to flow inside the shed again and to accelerate the yarn. Starting from the state of the art metal strip shape and taking into account the results gained by means of flow field simulation, a new geometry of metal strip has been developed by means of a parametric study on the geometry of the metal strip. As a result of the CFD simulation, the power of the flow is depicted in Fig. 10.

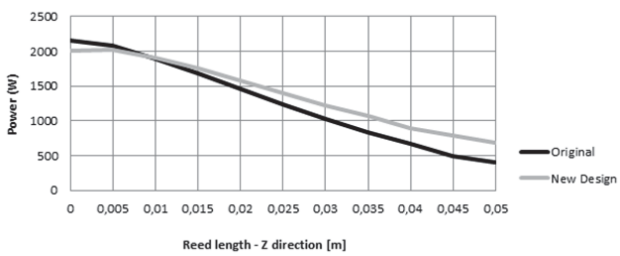

Fig. 10 Flow power along the shed at three bar inlet overpressure

The design of the new metal strip allows higher values of the flow power that are transmitted to the filling yarn. Therefore, it would be possible to transmit the same amount of propulsive force to the yarn at a lower pressure value. Finally, the results of CFD have been validated by carrying out experimental measurements (Fig. 11).

The purpose of such measurements is to demonstrate that the new profiled reed can provide the same flow power to the weft yarn at a lower pressure (Fig. 12), hence by fostering energy savings.

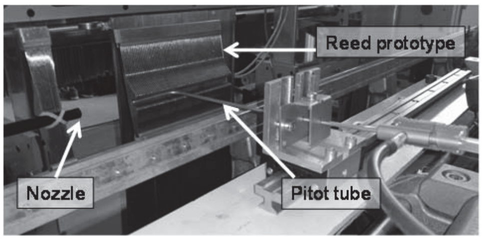

Fig. 11 Test bench set up with measurement devices

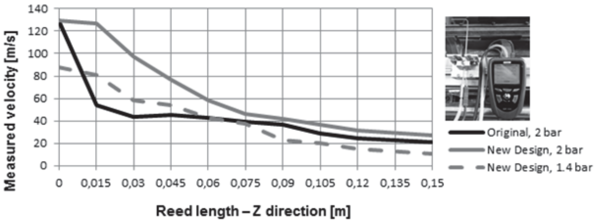

Fig. 12 Velocity profiles measured in the reed prototypes

The flow field along the newly designed shape delineates at 1.4 bar a similar velocity behaviour in comparison to the original prototype at a 2 bar inlet pressure value. This outcome can be usefully exploited by decreasing the working pressure of the machine, because the innovative concept of reed would provide, at 30% lower pressure, a similar performance in comparison with the original profile, therefore resulting in a decrease of the total cost of ownership of the machine.

V. Conclusion

Air-jet technology is the most productive, but also the most energy intensive weaving process. By placing the reduction of energy consumption as the central goal to achieve, the most energy demanding process and components are identified and analysed from the exergetic point of view. Based on a geometrical parametric study, a new concept for the metal strip of the profiled reed is designed. The new metal strip enables a reduction of the machine energy consumption and it forces a higher amount of the air to remain into the channel, as it prevents larger amounts of the flow to vanish through the front and through the backwards of the reed. Within the weaving process, the reed has a relevant influence on guiding the air flow, therefore the investigation of the flow field points out relevant remarks to use potential new geometries. The CFD simulations give a first deeper understanding on the interaction of the flow field along the shed. By taking into account the results of the parametric study and by following an optimisation procedure, a more energy efficient flow characterised by higher useful power can be achieved within the weft acceleration region. In order to validate the theoretical assumptions and the CFD simulations, experimental measurements are carried out on two reed prototypes. The measurements show that the newly designed component is more performing then the original configuration and the experiments confirm the theoretical hypothesis of achieving energy savings. It can be drawn that the innovative designed component provides higher flow velocities and mass flow rate values along the shed. Basically, by means of the innovative reed concept, higher values of the flow power are transmitted to the filling yarn. The measurements show that the innovative reed provides a similar velocity profile in comparison to the benchmark configuration, at about 30% less pressure supply. This outcome can be positively exploited by decreasing the inlet pressure of the relay nozzles whereas leaving constant the productivity of the machine. Consequently, the costs of the power and the energy consumption associated to pump up the air would largely decrease (Table IV). By taking into account the results drawn so far within the present study, it is expected that the innovative reed concept will be mounted on the air jet weaving machines of a weaving mill in order to figure out, measure, and validate on large industrial scale the real energy savings rate.

TABLE IV
ENERGY CONSUMPTION OF A COMPRESSOR [2]

Operation Pressure [bar]	Energy consumption [kW/m³/h]
1	2.8
2	3.56
3	4.12
4	4.72
5	5.35

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