23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

INCREASING ENERGY SAVINGS POTENTIALS OF AIR-JET WEAVING MACHINES BY USING ENERGY EFFICIENCY AS A CENTRAL REQUIREMENT IN THE DESIGN PHASE OF THE WEFT INSERTION PROCESS

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Abstract. *The use of a novel method to exploit energy savings potentials in production processes of textile industry has been applied to the air-jet weaving technology. Energy efficiency is taken as central property in the design process and it represents a new requirement/property to be defined in the phase of design problem/task definition. In contradiction with established methodologies, the approach 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 and processes are afterwards systematically addressed to reduce their energy consumption: interaction of the relay nozzle flow field with the profiled reed. A following analysis step consists in the verification of the system design, predicting and evaluating the system behavior using several tools (e.g. finite element analysis, computational fluid dynamics simulations, experimental analyses, etc.). 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, able to decrease the environmental impact and to keep constant the machine performance requires an integrated research strategy. Therefore in next air jet weaving machine generations, the design process should move from a purely performance and capacity driven approach to an approach that includes energy efficiency as a key parameter.*

Keywords: *Energy efficiency, air jet weaving, weft insertion, machine manufacturing, simulation and experimental analysis*

1. INTRODUCTION

Air-jet weaving is a type of weaving in which the filling yarn is inserted into the warp shed with compressed air. Figure 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, where the relay nozzles provide the high air velocity across the weave shed. Profiled reed provides guidance for the air and separates the filling yam from the warp (Adanur, 2001). A cutter is used to cut the yarn when the insertion is completed.

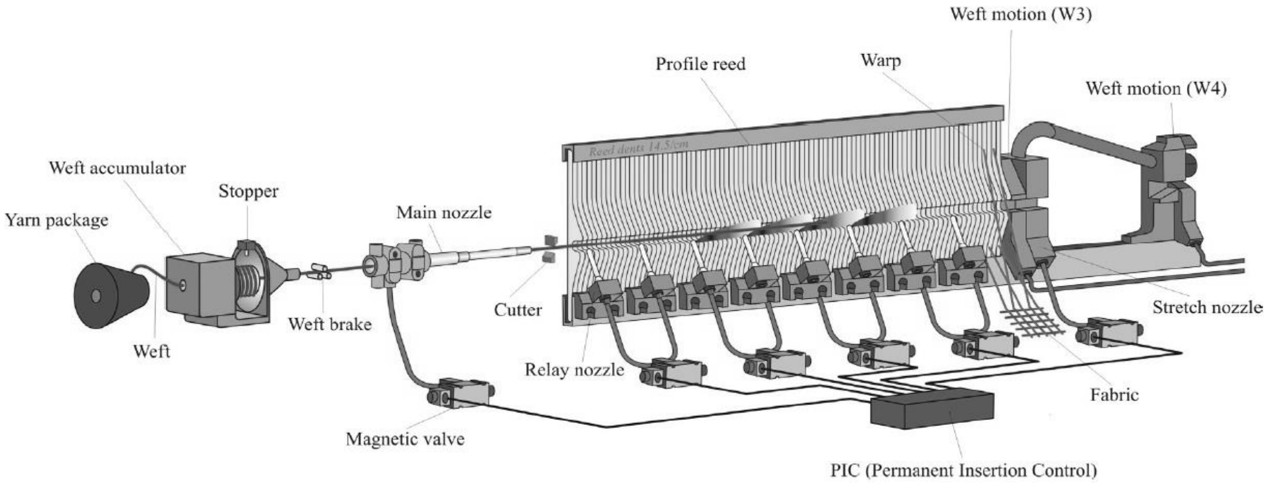

Figure 1. Schematic view of air-jet weft insertion system

The air-jet weaving machine combines high performance (see Tab. 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.

Table 1. General Characteristics of Air-Jet weaving machine

Air Jet weaving machine	
Weft Insertion rate	2000 m/min
Average Specific Energy consumption (kWh/kg of woven fabric)	3 – 5 KWh/kg

Despite the very high production rate, the main drawback affecting negatively this technology is the very high energy consumption (see Tab. 2) due to compressed air demand which is required during the weft insertion process (Schröter, A. 2014) 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 textile production machine manufacturers. In particular it is the limiting factor for such technology in the countries, where energy costs represents a large share of the manufacturing costs. An Overview of the manufacturing cost of a woven fabric can be seen in Tab. 2. (ITMF, 2008).

Table 2. Overview of the manufacturing costs of a woven fabric

	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

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, but 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.

At the purpose of decreasing the waste of compressed mass flow rate along the shed, a novel method based on energy efficiency as a central requirement in the design phase has been developed at the Institut für Textiltechnik der

RWTH Aachen University (ITA), Aachen, Germany. Such method aims at increasing the energy efficiency of the machine by increasing the effective amount of mass flow rate which is directly involved in the weft insertion process. The increase of the mass flow rate in the air tunnel is rising the productivity of the machine while keeping constant the quality of the fabric. The study focuses on the interaction of the flow field coming out of the relay nozzles with the metal strips of the profiled reed. A detailed picture of the position of the relay nozzles and of the profiled is shown in the following Fig 2.

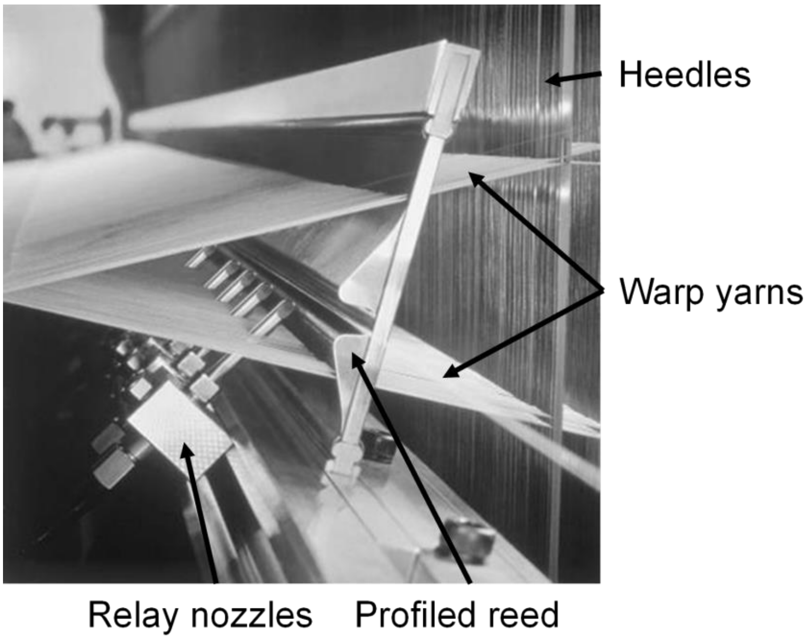

Figure 2. Detailed view of the relay nozzle and the profiled reed

Finally, the result of the research led to the investigation of the flow field throughout the shed and it gives a valuable insight for the design and development of a new air tunnel shape, able to decrease the waste of air and to provide higher propuslive force to the filling yarn and therefore increasing the productivity of the machine. In this way, the high cost of the compressed air is justified by an achievement of higher value of the machine productivity.

2. 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. Theories and models of technical products and product development process have been in the focus of scientific work for roughly 40-50 years. Today, they are increasingly relevant also in industrial application (including machinery) because they are vital elements of current strategies such as concurrent / simultaneous engineering. Design for “X” (with “X” = strength, manufacturing, assembly, service, recycling, cost, etc.) is an important strategy especially in engineering design practice: the introduction of energy requirements into product specification can lead to define approaches of Design for energy efficiency.

Until now very few structured approaches for machinery design that take into account the energy impact of the resources 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 textile machines (Schröter, A. and Grassi, C., 2015). Established design methodologies have not yet considered energy efficiency as a central requirement of technical systems. As an inherent part of the methodology, it is necessary to take energy efficiency as a central requirement into account, like the static, the dynamic or the thermal behavior of a machinery.

A systematic approach for the development of energy efficiency machine tools, proposed by Neugebauer (Neugebar, 2010), provides general concepts that can be applied to other type of industrial machinery and could be taken as reference in the possible definition of methodologies for the energy efficiency design of specific machines. This approach is based on the property-driven design methodology (see Fig. 3) by Weber (Weber, 2007), that defines the design process as a process which has to reach given properties (i.e. requirements) by defining characteristics to ensure this properties (e.g. geometries or materials).

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 (see Fig. 4) includes an initial analysis of existing technical systems and the individuation and classification of their prior and relevant energy consumers (sub-systems and processes).

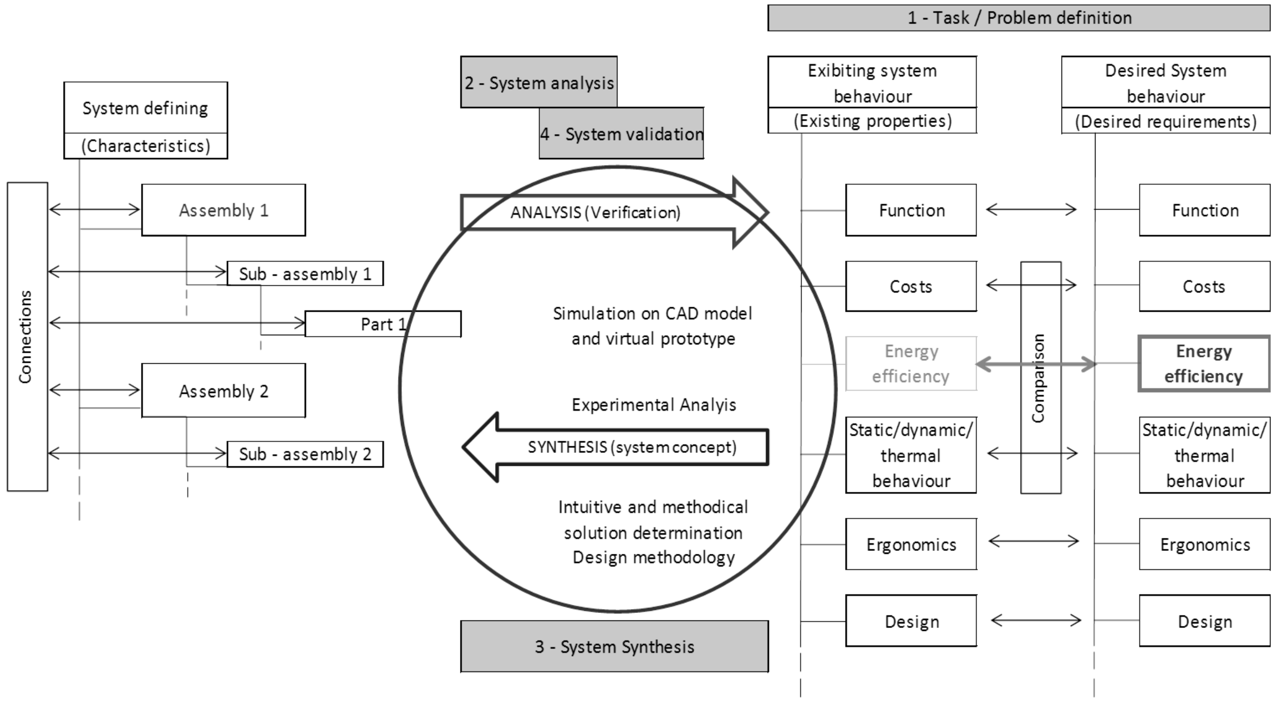

Figure 3. Property-driven development by Weber

The identified major consumers are afterwards systematically addressed to reduce their energy consumption: several options and solutions – the system characteristics – are determined and considered, starting with the complete elimination of the energy usage and ending with the option of recovering energy. A following step of analysis consists of the verification of the system design, predicting and evaluating the system behavior using several tools (e.g. FEM analysis, simulation models, experimental analyses, etc.). The design process provides one or more solutions if the accounted properties are met by the defined characteristics.

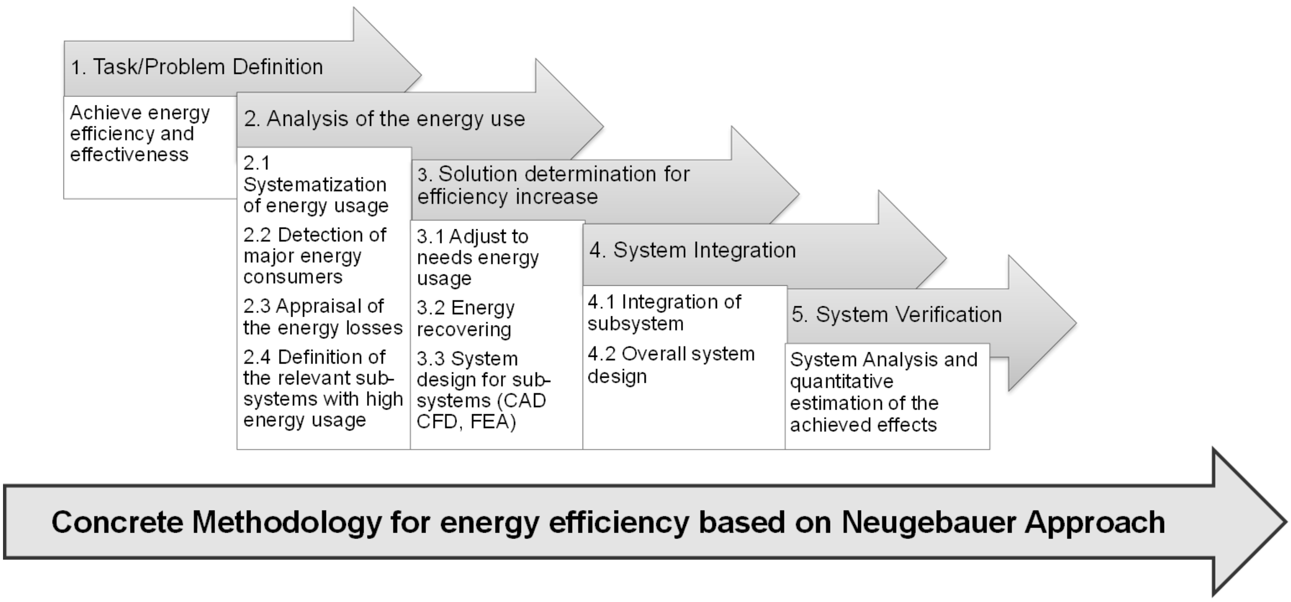

Figure 4. Methodology for energy efficiency

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. A systematic machine design approach has to take into account both the machine tool performance and the energy efficiency.

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 and what will be the associated total cost of ownership and environmental impact. 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, able to decrease the environmental impact and to keep constant the product quality requires an integrated research strategy.

2.1 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. These metal strips are evenly spaced at 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. The shape and thickness of the metal wires used in the reed are important parameter for the fabric features. Reed selection 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 process, most of the air injected by the relay nozzles (more than 50%) leaks throughout the reed and only a small percentage of air, about 30%, is actually accelerating the yarn and driving it to the receiving side of the machine. This matter turns into a large energy inefficiency of the machine by considering the unexploited amount of air that could improve the productivity of the air jet weaving machine in terms of weft insertion per minute and by taking into account the cost associated to the compressors in order to pump up most of the air that is not actually exploited. On a large industrial scale, such inefficiency mirrors into a relevant increase of the total cost of ownership of the machine. Therefore, at the purpose of justifying the high cost related to the compressed air, an investigation of the flow field along the reed has been carried out in order to reduce the waste of the mass flow rate leaking through the reed and in turn by increasing the amount of air which positively contributes to the yarn motion (see Fig. 5).

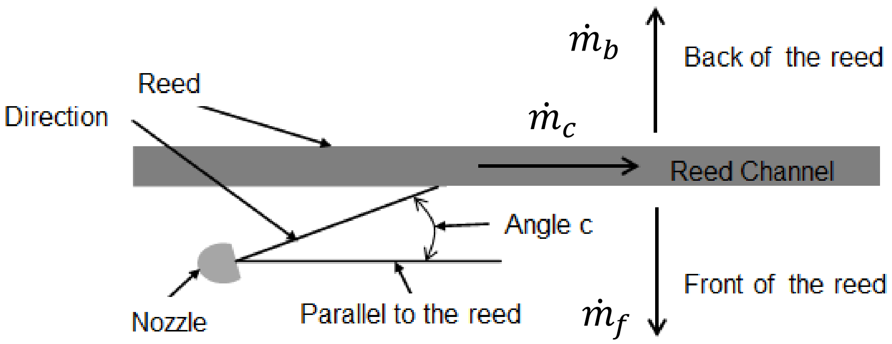

Figure 5. Theoretical model of the weft insertion process in air jet weaving machines

The propulsive force to move the yarn in the reed channel is provided by the friction between the air and the yarn surface and is given by the following Eq. (1),

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

With

C_f = skin friction coefficient
ρ = air density
U = air velocity
V = yarn velocity
D = yarn Diameter
L = yarn length subject to air, yarn characteristic length

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 it depends on the amount of mass flow rate coming out from the relay nozzles too. To increase the value of mass flow rate in the reed channel means to increase the productivity of the machine.

Assuming the further hypothesis:

- Steady state flow
- Negligible yarn flexibility
- Constant yarn velocity across the shed
- Interaction of air through the reed dents

The thrust provided by the relay nozzles to the yarn is the key point 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 study carried out at ITA gave a valuable intuition to build up a new geometry of the metal strip, based on the aerodynamic duct theory in order to minimize the amount of waste air and in turn to maximize the number of weft insertion per minutes. Characteristic of this new shape is the more enclosed structure which prevents air to get out of the reed and it fosters an increase of the mass flow rate which is really participating to the propulsive force on the yarn. By employing the new concept of metal strip, the velocity of the yarn, which is currently in the state of the art between 55 m/s and 80 m/s, is increased and the weft insertion rate per minute rises of 10%. The model in Fig. 5 is a reasonable first approximation and it gives an insight to understand the physics of the air jet weft insertion process. Consequently, deep aerodynamic simulations have been carried out in order to validate the theoretical model and to provide a more faithful representation of the flow field coming from the relay nozzles along the shed.

3. RESULTS

For the validation of the theoretical model different, flow simulations have been carried out. The simulations are done with the Computational Fluid Dynamics (CFD) simulation tool ANSYS Fluent from ANSYS, Inc., Canonsburg, USA. Within the simulation the flow field along the shed and the interaction with the reed is simulated and analyzed. 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 was integrated into this model. Downstream of nozzles is a free flow field with ambient pressure. The CFD model with the simulated flow field is shown in Fig. 6.

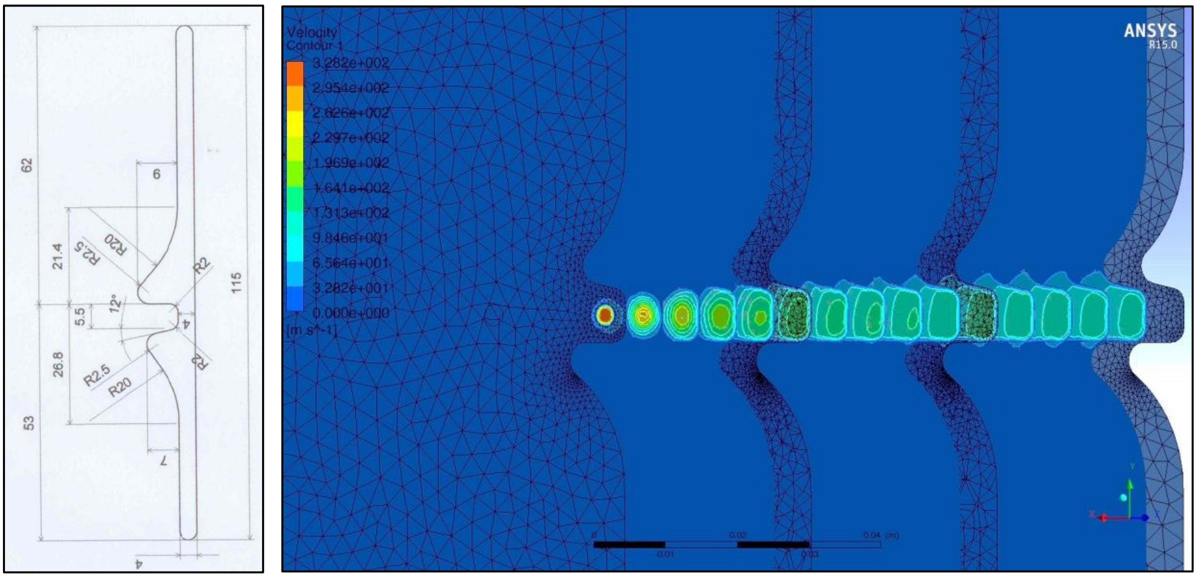

Figure 6. Shape of the metal strip and flow field simulation along the air tunnel

The air stream that lies in the air tunnel escapes from the acceleration region of the yarn not only towards the forward open side of the reed channel, but also through the back. According to the fluid-dynamic theory, the air flows quite in the middle of the channel. Moreover it can be drawn by means of the simulations 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. The velocity circles identify the velocity flow field and by going along the shed it can be seen that such circles move towards the wall, between the void spaces in the dents. Such air afterwards therefore is wasted and no longer able to go 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 therefore developed in order to cope with this issue (see Fig. 7).

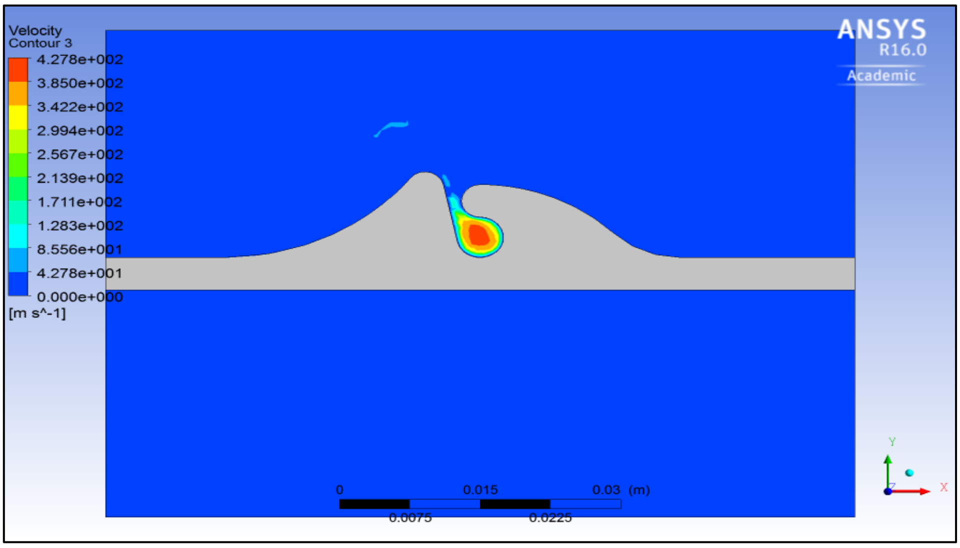

Figure 7. New shape of the metal strip which enables potential savings of compressed air

This new more enclosed shaped metal strip is capable to hold an higher quantity of air inside the air channel and therefore to increase the friction with the yarn. The rise in the friction force mirrors into an increase of the number of picks per minute. In this way, the costs associated to the compressors can be better justified, since more air is remaining in the air channel and the productivity of the machine increases of a factor 10%.

4. DISCUSSION

The simulation of the flow field along the shed show that energy savings are possible by employing a new metal strip shaped geometry. Such geometry prevents air to vanish towards the front of reed and it enables a rise of the machine productivity. The enclosed geometry gives an higher thrust to the yarn which mirrors in a rise of 10% of weft insertion picks per minute. Within the weaving process, the reed has a relevant influence on the flow field; therefore the investigation of the flow field carried out in this study, gives a relevant remark to use potential new geometries of profiled reed. Nowadays, considering the weaving process, the relay nozzles employ 5 bar in overpressure: by combining this study on the reed with the investigation carried out on the relay nozzles, another noticeable remark can added to justify the reduction of the inlet pressure in the relay nozzles, since such rise in the pressure is made basically just to increase the mass flow rate in the air-channel. Of course the flow field out of the nozzles is strictly connected to the flow behavior in the reed and other studies have been made at ITA concerning this matter (Schröter, 2014).

Eventually, by using the new shape of metal strips in combination with a new concept of relay nozzles able to operate at a lower value of inlet pressure, not only the productivity of the machine is improved but also the costs associated to pump up the air are reduced. The use of smaller compressors (see Tab. 3) enables a relevant reduction of the energy consumption of the weaving machine, without negatively affecting the quality of the fabric.

Table 3. Energy consumption of a compressor depending on the operating pressure

Operation Pressure [bar]	Energy consumption [kW/m³/h]
1	2,8
2	3,56
3	4,12
4	4,72
5	5,35

In the case of 5 bar operating pressure the compressor has an energy consumption of 5,35 kW/m³/h. If the operation pressure will be reduced to 1 bar, the energy consumption is 2,8 kW/m³/h. By employing the combination of new shaped reed with a new concept of relay nozzles able to operate at 1 bar, energy potential can lead up to 30% savings.

5. CONCLUSION

At the Institut für Textiltechnik der RWTH Aachen University, Aachen, Germany a novel method has been developed to identify potentials in saving energy of textile production processes (Schröter, A. and Grassi, C., 2015). The air-jet weaving process is the most productive but also the most energy intensive weaving process. By placing energy efficiency as a central requirement in the design phase of the machine, the most energy demanding processes and the components are identified and analysed. Based on a theoretical model of the weft insertion, a new concept for the metal strips of the profiled reed has been drawn. The new metal strip enables an higher quantity of air to remain longer in the air tunnel where the filling yarn is flying. Such increase of mass flow rate turns into an improvement of the machine performance, 10% in terms of weft insertion picks per minute. Moreover, such new geometry allows the use of new relay nozzles concept which are able to operate at a reduced inlet pressure value. By combining the application of new profiled reed with new concept of relay nozzle able to operate at 1 bar, not only the total costs of machine ownership are reduced but also the productivity is increased. By means of CFD simulations, this study gives a first insight on how to improve the usage of compressed air during the weft insertion process. The next step is the validation of the new profiled reed concept before by means of a test bench and afterwards on a larger scale within the real weaving process.

5. ACKNOWLEDGEMENTS

The European Commission is gratefully acknowledged for its support of the Marie Curie program through ITN EMVeM project, Grant Agreement N° 315967.
The project VIP0477 is in the form of assistance "Validierung des innovationpotenzials wissenschaftlicher Forschung - VIP" is supported by the Federal Ministry for Education and Research.

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