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Redesign of steam turbine rotor blades and rotor packages – Environmental analysis within systematic eco-design approach

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ABSTRACT

Eco-design of steam turbine blades could be one of the possibilities of decreasing the environmental impact of energy systems based on turbines. The paper investigates the eco-design approach to elaboration of the rotor blades and packages. The purpose is to present the course of eco-design of the rotor blades and the rotor packages taking account of eco-design assumptions, solutions and the concept itself. The following eco-design variants of the rotor blades and the rotor packages are considered: elements of the rotor blades made separately (baseline variant of the rotor blades); elements of the rotor blades made of one piece of material; blades in packages made separately and welded (baseline variant of the rotor packages); packages milled as integral elements. At the stage of detailed design, the Life Cycle Assessment (LCA) is performed in relation to a functional unit – the rotor blades and packages ready for installation in a steam turbine, which is the stage of the turbine. The obtained results indicate that eco-innovative solutions for the turbine blades and packages could be achieved through structural and technological changes. Applying new solutions of the rotor blades may produce the following main benefits: 3.3% lower use of materials, 29.4% decrease in energy consumption at the manufacturing stage, 7.7% decrease in the environmental impact in the life cycle. In relation to the rotor packages, the following main benefits may be achieved: 20.5% lower use of materials, 25.0% decrease in energy consumption at the production stage, 16.2% decrease in the environmental impact in the life cycle.

1. Introduction

1.1. Reasons for research and the solution novelty

Existing power plants are equipped with old, even 50-year-old turbines, whose parts need to be repaired and/or replaced. The significance of the problem is illustrated by the quantitative scale – steam turbine plants remain the most common type of systems used for combined production of electricity and heat [1–3], which is often justified economically. It also has to be remembered that steam turbines generally have a complex nature comprising multi-stage steam expansion to increase thermal efficiency [4].

This creates a potential for research aiming not only to achieve higher efficiency but also to reduce the environmental impact of energy generation systems [5,6]. In this context, this study fits in sustainable power generation research related to analyses of environmental aspects in numerous Life Cycle Assessment (LCA) studies that have been conducted for electricity generation systems, e.g. [7–10].

Blades are critical components of steam turbines and they are susceptible to failure due to stresses arising primarily from centrifugal loads and bending forces related to the steam mass flow [11]. Moreover, corrosion, leading to crack initiation and propagation, is an important failure mechanism in blades [12]. This means a need to replace them during repair or overhaul works and may necessitate redesign of the elements.

According to Shimoyama et al. [13], in order to design a highly efficient steam turbine, it is essential to consider many design objective functions regarding the fluid dynamic performance (energy loss reduction, smooth guidance of working steam, etc.) simultaneously. In addition, the steam turbine has a number of geometric and topological variables (blade shape, number of blades, number of stages, etc.) that also have to be taken into account at the design stage at the same time [13].

This set of variables is extended in the eco-design approach aiming to find eco-innovative solutions due to the application of eco-design rules. Such an approach concerns the production,

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Nomenclature

AISI	American iron and steel institute
CAD	computer-aided design
CED	Cumulative Energy Demand
CNC	computerized numerical control
DALY	Disability Adjusted Life Years
DUPLEX	steels with a >16% content of chromium, a nickel content of 4–6% and a molybdenum content of 1.5–3%
Ecoinvent	Life Cycle Inventory database developed by the Swiss Center for Life Cycle Inventories
ELCD	European reference Life Cycle Database established by the European Commission's Joint Research Center
eq	equivalent
EUROFER	European steel association
GHG	greenhouse gas
Idemat	database developed by the section for environmental product development of the faculty of industrial design engineering at the Delft University of Technology in the Netherlands
IMPACT 2002+	IMPact assessment of chemical toxics – impact assessment methodology developed by the Swiss Federal Institute of Technology
ISSF	International Stainless Steel Forum
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PDF	Potentially Disappeared Fraction
pers × y	unit of normalized impact generated by a given number of persons during 1 year
PM2.5	particulate matter with a diameter of 2.5 μm or less
TEG	triethylene glycol
TIG	tungsten inert gas
v	version

assimilation or exploitation of a product, the production process, service, management or business method that is novel to the organization (developing or adopting it) and results, throughout the product life cycle, in a reduction in the environmental risk, pollution and other negative impacts of the use of resources (including energy consumption) compared to relevant alternatives [14,15].

The novelty of the solution proposed herein lies in the inclusion of environmental aspects in the steam turbine blades design. This is a challenge both to individual companies and to the power sector in general. On the organization scale, the search for and development of new design solutions is therefore supplemented with an analysis of environmental parameters, which may be of interest to customers. When it comes to issues related to power generation, it has to be stated that many studies are undertaken to improve the performance as well as the structural and technological parameters of the energy generation system components. This paper proposes a view of the power engineering system as a structure where the life cycle characteristics may have an effective influence on the improvement in the system environmental parameters. Such an attitude of a systematic inclusion of environmental aspects in the design of the turbine components such as the rotor blades and packages is unique against the background of other research trends and may contribute to an improvement in environmental parameters along the supply chain and better communication between the chain links.

1.2. Eco-design implementation issues in the company

Eco-innovation is a function of many factors. It seems that the decisive ones are the business aspects [15], but in practice the design office efficiency is also very important. This concerns methodological issues of the inclusion of environmental aspects at different stages of the design process, the selection of eco-design assistance tools and their use. This is the area where the knowledge gap is identified. The gap may be eliminated through a systematic approach to the analysis of environmental aspects within eco-design. At the same time, it is necessary to overcome a number of problems related to eco-design implementation.

First, Kaebernick et al. [16] state that adding environmental aspects to the product design and development in terms of the life cycle shows a new way of thinking that needs new tools and methods at each step of eco-design. In this context, a major challenge is posed by the need to construct a structural framework that will be used effectively in eco-design in a specific research area.

Moreover, in the selection of alternative design variants, environmental requirements should be considered as equal to other criteria. The reason for that are the rising concerns over escalating emissions, resource depletion and other environmental issues that lead to an increased emphasis on the design and manufacture of environmentally benign products [17,18].

As indicated by Stevels [19], there is disagreement between the academic and practical approach to eco-design. A lot of eco-design procedures and tools, in spite of their number and range of applications, are developed as theoretical methods not verified in industrial practice. Very often, due to their extreme complexity, lack of knowledge and the fact that they are rather time-consuming, the methods are not used by companies systematically [20].

Lofthouse [21] points to the role of industrial designers in implementing eco-design assumptions because they have a real influence on the product development in the early stages. That is why their decisions are so significant. According to Lofthouse [21], designers involved in eco-design look for information about supporting the operational area of eco-design to help them to turn ideas into reality.

Additionally, Vallet et al. [22] claim that environmental assessment, solution finding and strategy definition are the activities which differentiate eco-design from design, and that environmental initial assessment and strategy definition are more heavily influenced by eco-designers' expertise than support from tools. Confirmation of these claims can be found in the findings presented herein. The need to resolve the eco-design paradox is also taken into account. According to the paradox, the chance of improving a product in terms of its environmental impact decreases as the eco-design process proceeds, i.e. the later the analysis of environmental aspects is undertaken, the smaller the chance to introduce essential changes in the environmental profile [23].

The analysis presented in this paper takes account of the aspects mentioned above. They are therefore the inspiration for a systematic inclusion of environmental aspects in the steam turbine blades design.