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## Shape design of internal cooling passages within a turbine blade

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### Abstract

The [article](#) concerns the optimization of the shape and location of non-circular passages cooling the blade of a gas turbine. To model the shape, four Bezier curves which form a closed profile of the passage were used. In order to match the shape of the passage to the blade profile, a technique was put forward to copy and scale the profile fragments into the component, and build the outline of the passage on the basis of them. For so-defined cooling passages, optimization calculations were carried out with a view to finding their optimal shape and location in terms of the assumed objectives. The task was solved as a multi-objective problem with the use of the Pareto method, for a cooling system composed of 4 and 5 passages. The tool employed for the optimization was the evolutionary algorithm. The [article](#) presents the impact of the population on the task convergence, and discusses the impact of different optimization objectives on the Pareto optimal solutions obtained. Due to the problem of different impacts of individual objectives on the position of the solution front which was noticed during the calculations, a two-step optimization procedure was introduced. Also, comparative optimization calculations for the scalar objective function were carried out and set up against the non-dominated solutions obtained in the Pareto approach. The optimization process resulted in a configuration of the cooling system that allows a significant reduction in the temperature of the blade and its thermal stress.

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Keywords: shape optimization, evolutionary approach, blade cooling, multi-objective optimization

### 1. Introduction

The increase in the efficiency of energy generation in systems with a gas turbine involves, first and foremost, the increase in the gas temperature at the turbine inlet. At the moment the opportunities to improve this parameter are very limited, mainly due to reasons related to the material, and a further progress in this field requires a simultaneous development of three interacting areas of research. These are:

- search for new heat resistant materials for the components working at the inlet part of the turbine
- improvement in thermal and environmental protective coatings
- continuous improvement in the techniques of cooling high temperature components

The use of modern materials makes it possible to raise the temperature of a component to a level arising from the thermal limits of the materials they are made of. A negative effect of the

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1  
2 use of the most advanced materials for high temperature components of gas turbines is usually  
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4 the significant investment cost of this solution. In the case of the use of cooling systems of  
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6 components the situation is slightly different. Here, in addition to the investment aspects  
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8 (higher costs of manufacture of the components with cooling systems), other issues will play a  
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10 significant role, such as problems of a mechanical nature, flow problems, the negative impact  
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12 of the cooling on the efficiency of the thermal cycle of the turbine or, finally, the level of  
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14 emission of pollutants (Glezer, 2001). The use of cooling systems allows a significant  
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16 increase in the gas turbine working temperature, and an appropriate design of the specific  
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18 cooling system makes it possible to additionally reduce the negative impact of their presence  
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20 on the operation and life of the machine. This is why for many years now there has been an  
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22 intensified scientific and research activity in the field of cooling systems, which results in a  
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24 continuous increase in the working temperature of gas turbines used both in the power  
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26 industry and aviation.

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27  
28 Nowadays cooling systems of gas turbine blades make use of passages with complex shapes  
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30 of cross-sections in order to most effectively reduce the temperature of the component  
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32 material, maintaining the technological, mechanical, and flow objectives. For  
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34 aerodynamically optimized profiles, the cooling passages can take strange shapes (Weigand,  
35  
36 2001), which in many cases reflect the local geometry of the blade. Moreover, the passages  
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38 for inner cooling are fitted with various turbulizers whose task is to intensify the heat  
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40 exchange process. Also, inner cooling is usually accompanied by film cooling, whose task is  
41  
42 to create a thin film of cool gas (cooling air) around the profile, and, at the same time, to  
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44 separate the hot working agent from the blade material. In some solutions, in order to  
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46 intensify the cooling of the leading edge of the blade (usually the most thermally loaded area)  
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48 impingement cooling is applied (Han, 2004).

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2 A detailed analysis of thermal and flow phenomena which take place during the cooling  
3 mechanisms mentioned above is a major computational challenge. The main difficulty is to  
4 determine the boundary conditions in the passages, *i.e.* to estimate the coefficients of heat  
5 transfer and of the coolant local temperature. This is due to the complex shapes of the  
6 passages with neckings and reversals which often contain turbulizing elements. Because of  
7 this, it is very difficult to define precisely the value of the local heat transfer coefficient, or the  
8 level of the cooling air temperature in various zones of the passage. A solution here is to  
9 perform Conjugate Heat Transfer simulations. However, these analyses are computationally  
10 expensive and they usually call for considerable model simplifications. Some attempts to  
11 solve the conjugate task for cooled blades were presented in the works of Facchini *et al.*  
12 (2004), Hong *et al.* (2004), Montomola *et al.* (2004). Similar issues are discussed by Fedruzzi  
13 and Arts (2004) for finned cooling passages, and Kusterer *et al.* (2004) for film cooling.  
14 Obviously, the problem gets much more complicated when several cooling mechanisms are  
15 combined.

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## 2. Optimization of the cooling system

31 Cooling of heat turbine components, including blades, is inseparably connected with  
32 loss generation which results from the flow of the cooling agent. The structure of the cooling  
33 system, and consequently the flow rate of the cooling air, significantly influences the total  
34 efficiency of energy conversion in the system. On the other hand, the cooling system used  
35 should make sure that the maximum temperature of the component being cooled is kept below  
36 the permissible temperature level. The value of the permissible temperature depends on the  
37 material used, and corresponds to the melting temperature, and the thermal and creep strength  
38 of the material. The material properties mentioned above are determined on the basis of  
39 experimental research.

Thus the right choice of the cooling system is connected with conducting an optimization process to find such a system configuration that will ensure compliance with the basic economy and strength objectives. These objectives are as follows (Bunker, 2006):

- to maintain the blade temperature at a permissible level,
- to reduce the coolant mass flow,
- to keep stresses at a safe level,
- to secure the proper durability of the element,
- to secure the proper rigidity of the component.

It is only in recent years that scientists became interested in the problems of optimization of the cooling systems of gas turbine blades. This situation results from the high cost of optimization calculations. Lack or unavailability of high-performance computing machines precluded, until recently, the modelling or conducting appropriate calculations. A substantial increase in the computing capacity of PCs and the development of parallel processing techniques made it possible to deal with the problem on a bigger scale. Optimizing calculations concerning the components of the flow system of a turbine (e.g. blades) mean having to carry out multiple flow and thermal analyses or conjugate tasks.

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The attempts to find the optimum choice of the cooling system made recently were focused mainly on convection cooling with the use of inner cooling passages. At the moment it is probably the only cooling mechanism that can be analysed as a whole. External cooling systems, because of the complexity of the phenomena taking place, are only analyzed for calculations of the "given state" (Garg, 2002), and only some secondary aspects are the subject of optimization, e.g. the outflow of the agent from a single hole in film cooling. Talya et al. (1999, 2002) took film cooling into consideration in the process of the profile shape optimization, but its structure was invariable; so were the shapes of the inner passages, which were only scaled according to the size and shape of the profile. For several years now Dulikravich and his team (Martin and Dulikravich, 2001, Jeong et al., 2003, Dennis et al., 2003a, b) have been doing research on various problems concerning optimization of turbine

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2 blade cooling with focus on flow, thermal, and strength objectives. The outcome of that  
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4 research is the Multidisciplinary Computer Automated Design Optimization (MCADO). The  
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6 works are mainly concerned with optimization of the inner cooling passages (Dennis *et al.*,  
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8 2003a, Martin *and* Dulikravich, 2001) with a possible outflow of the cooling air at the trailing  
9  
10 edge of the blade (Dulikravich *et al.*, 1999). It can be observed in these works that, in spite of  
11  
12 numerous design variables used in the calculations, the optimization process is strongly  
13  
14 restricted with relation to changes in geometry, *i.e.* optimization affects, for example, the fillet  
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16 radius of the passage, the distance between the passage and the wall, or the interspacing of the  
17  
18 passages. In their next work (Dennis *et al.*, 2003a) the authors presented optimization of the  
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20 location of a large number of cooling passages with a circular cross-section. The location of  
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22 these channels, however, was restricted to a narrow area of the blade section close to the blade  
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24 wall. The object of the task studied in that work was to find a pattern for the distribution of  
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26 the cooling holes so that the heat flux absorbed by the coolant could be maximally reduced,  
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28 with the temperature of the blade maintained at permissible level, and so that the amount of,  
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30 in this case, steam necessary for the cooling could be reduced, too. Dennis *et al.* (2003b)  
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32 presented another interesting work on the optimization of the cooling passages in the shape of  
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34 a serpentine with three returns of the cooling agent. The problem was dealt with in the 3-D  
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36 system with the use of thermal and strength objectives. The obtained results revealed a great  
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38 potential in the cooling system; the proper selection of the shape and distribution of cooling  
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40 passages has a substantial impact on the consumption of the cooling agent, the thermal stress,  
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42 and, consequently, the increased durability of the blade.

43  
44 Optimization of inner cooling passages was also the interest of Haasenritter *and*  
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46 Weigand (2004), but they considered the problem from the point of view of the selection of  
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48 the structure of cooling fins turbulizing the flow. They analyzed a section of a passage with  
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50 set dimensions, from the walls of which there protruded rectangular (2-D analysis) fins  
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2 causing obstacle to the flow of the cooling agent. The authors looked for the best fin  
3 configuration (interspacing, width and height) to optimize the heat transfer in the passage.  
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6 Nowak ~~and~~ Wróblewski (2009) presented optimization of the distribution and radii of circular  
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8 cooling passages inside the turbine blade according to the thermo-mechanical objectives. In  
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10 this case the approach was that the cooling holes could move freely in the blade cross-section;  
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12 the only restriction was to retain the feasibility criteria.

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14 The problems of the optimization of the cooling systems for the blades of heat  
15 turbines usually involve a relatively large number of design variables together with a  
16 complex, non-overt, and sensitive to even small changes in parameters, response (function) of  
17  
18 the system under analysis. That response, e.g. in temperature, stresses or other values, is not  
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22 monotonic; it is characterized by a great number of (local) extremes, which is a major  
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24 problem for many optimization methods based on the gradient approach (Mueller, 2002). In  
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26 these situations stochastic methods are preferred, which in fact can be noticed in all the works  
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28 cited. The most often used is the evolutionary approach, which, in spite of its downsides (a  
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30 large number of evaluated solutions), is perfectly suited for dealing with complex technical  
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32 problems. This optimization method was chosen for this work.

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### 3. Modelling the shape of the passages with the use of Bezier curves

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35 The object of this study was an attempt to design an internal cooling system for gas  
36 turbine blades on the basis of non-circular cooling passages. The task consists in an optimal  
37 selection of both the location and the shape of individual passages, and a single optimization  
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39 problem is run for the number of passages inside the blade material assumed by the user. The  
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41 design task was carried out in this study for profile C3X available in the literature (Hylton et  
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45 al., 1983), which originally is cooled with 10 cylindrical passages.  
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2 For the purposes of this work, Bezier curves were adopted to model the cooling holes  
3 of non-circular shapes. A Bezier curve is built of Bezier segments, each of which is defined  
4 unequivocally by four control points.  
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8 A cooling passage should be modelled with a smooth curve, which justifies the use of Bezier  
9 curves in this case. This approach makes it possible to define the location and shape of the  
10 hole with a relatively small number of variables, which is absolutely essential if evolutionary  
11 algorithms are used for optimization. The smaller number of estimated values is reflected in  
12 the shortening of the genotype encoding a single individual.  
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18 In order to obtain holes properly "matching" the cross-section of the blade, four Bezier  
19 segments were used to model each of them. Two of them (referred to as upper and lower)  
20 were to reproduce the shape of the blade profile, whereas the other two (right and left) were to  
21 close the profile of the cooling hole (as shown in Fig. 1).  
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26 As was mentioned before, a single segment is based on four control points, but  
27 because of the joining of individual segments into a closed curve, some of the points coincide.  
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29 In the presented approach, in order to reduce the number of variables, and to simplify the  
30 procedure, it was additionally decided that the second and the third point of the upper and  
31 lower segment coincide as well.  
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36 Eventually, the modelling of a single cooling hole requires the determination of 10  
37 control points, and consequently 20 coordinates. In this [article](#) the coordinates of all points are  
38 determined on the basis of 8 values ( $n_{1s}$ ,  $n_{2s}$ ,  $q_1$ ,  $q_2$ ,  $q_3$ ,  $q_4$ ,  $q_5$ ,  $q_6$ ), which in this case are  
39 estimated values. A sample cooling passage with marked control points and estimated values  
40 is shown in Fig. 1.  
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45 The first two estimated parameters  $n_{1s}$ ,  $n_{2s}$  are natural numbers (between 15 and 80),  
46 which are equivalents to the node numbers on the upper edge of the blade (hence the  
47 restriction). On their basis the corresponding nodes ( $n_{1p}$ ,  $n_{2p}$ ) on the lower edge of the profile  
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2 are found. The corresponding node is one closest to the normal line to the upper edge of the  
3 blade and drawn through a given node on the upper edge of the profile. Between nodes  $n_{1s}$   
4 and  $n_{2s}$ , and their "lower" equivalents, an intermediate node is selected respectively, which  
5 causes that the first two estimated values define the location of 6 nodal points on the surface  
6 of the blade. Each of the nodal points on the upper part of the blade is then shifted to the  
7 inside of the blade by a normal vector of the length corresponding to the width of the profile  
8 multiplied by parameter  $q_1$ , the third design variable. The same is done for the points on the  
9 lower surface, except that they are shifted by a vector  $q_2 \cdot \overline{n_{1p}n_{1s}}$ , where  $q_2$  is the next (fourth)  
10 estimated parameter. The above operations result in the determination of the location of 6  
11 control points within the blade. On the basis of the first three of them ( $P_{21}$ ,  $P_{22}=P_{23}$  and  $P_{24}$ )  
12 the upper segment of the Bezier curve is defined, and on the basis of the other three – the  
13 lower one ( $P_{41}$ ,  $P_{42}=P_{43}$  and  $P_{44}$ ).  
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26 As mentioned above, due to the specific nature of the problem, the Bezier curve  
27 modelling the cooling passage must be a smooth one. A single segment which is a third  
28 degree polynomial meets such an assumption by definition, but this smoothness is not ensured  
29 automatically at the joining of two segments. An important issue is then to take care of the  
30 proper control point distribution which will ensure the existence of a derivative at each point  
31 of the curve (including the points of segment joining). It turns out that it is enough for the  
32 control points of the joined segments to be collinear. For example, adopting the designations  
33 as in Fig. 1, the collinear character of points  $P_{23}$ ,  $P_{24}=P_{31}$  and  $P_{32}$  ensures a smooth joining of  
34 the second (upper) and third (right) segment.  
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44 The next stage in the modelling of the cooling hole is the determination of the location  
45 of the remaining four control points (points  $P_{32}$ ,  $P_{33}$ ,  $P_{12}$ ,  $P_{13}$ ). To ensure a smooth joining, all  
46 the points must be located on appropriate straight lines. Point  $P_{13}$  is on the straight line  
47 passing through points  $P_{14}=P_{21}$  and  $P_{22}$ . Its coordinates are determined by shifting point  $P_{14}$   
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2 by vector  $q_5 \cdot \overline{P_{22}P_{14}}$ . Parameter  $q_5$  is another design variable. In the same way, with the use of  
3  
4 other design variables, the location of points  $P_{32}, P_{33}, P_{12}$  is determined. [More details](#)  
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6 [concerning this methodology](#) are given by Nowak and Nowak (2011).  
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#### 8 4. The optimization objective

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10 The optimization task discussed here is solved with the use of the evolutionary  
11 algorithm. This approach is based on the mathematical interpretation of the evolution process  
12 of living organisms, and, following the pattern of the biological process, it aims at  
13 "producing" individuals best adapted for the surrounding conditions. In optimization tasks  
14 these conditions are determined by task objectives on the basis of which individuals (problem  
15 solutions) are evaluated. The improvement in individuals is carried out by directed, slight  
16 changes taking place in their structure which result from the processes of mutation and  
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18 [crossover](#) known from biology.  
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25 Like in nature, the process of numeric evolution occurs in a population of individuals  
26 that are a potential solution to the optimization task. A single individual represents a set of  
27 characteristics which define the problem being solved. This information is most often encoded  
28 in its genotype either in a binary or a real number form. The latter was used in this [article](#) due  
29  
30 to the continuous character of the task. From the mathematical point of view, an individual is  
31 a vector whose components are design variables of the discussed problem. This means that a  
32 single individual defines the geometric configuration of the whole cooling system. Eight  
33 parameters are connected with each cooling passage, which means that for a system of five  
34 holes (the maximum considered case) there is a 40-dimensional design space to be dealt with.  
35  
36 Many practical problems cannot just be reduced to the objective function optimization task  
37 that returns a single value. Instead of one, numerical evaluation criterion, a few or more  
38 objectives have to be taken into consideration. Their simultaneous optimization is impossible  
39 for instance due to their mutual contradiction. For example, for the problem discussed in this  
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2 article, minimization of temperature generates an unfavourable increase in the stress of the  
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4 component.

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6 In this situation the problem is solved as a multi-objective optimization task. It is  
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8 obvious that in this case finding an unequivocally optimal solution is impossible, and  
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10 optimization consists here in searching for a group of solutions which are equally good  
11  
12 (acceptable) from the point of view of each analyzed objective.

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14 Therefore, the design task for a cooling system of a turbine blade was solved as a  
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16 multi-objective optimization problem with the use of the Pareto approach. The main aim of  
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18 the optimization task in question was to reduce the maximum temperature of the blade, with  
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20 thermal stress maintained at the assumed level, and with the lowest possible consumption of  
21  
22 the cooling agent. Generally, the presented partial objectives head for two opposite directions,  
23  
24 namely:

- 25 • decreasing the temperature of the blade results in stress increase, and requires a greater  
26  
27 flow of the cooling agent,
- 28  
29 • decreasing stress occurs at the expense of temperature, which rises because of less  
30  
31 intense cooling (decrease in the flow of the cooling agent).
- 32

33  
34 The thermal objective is in conflict with the two other ones, whereas the stress  
35  
36 objective is consistent with the objective of mass flow. This consistency, however, is not  
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38 unequivocal because for different configurations of the pattern of the cooling passages the  
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40 maximum stress values occur in different locations. Therefore it might turn out that the  
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42 solutions close to each other on the Pareto front, *i.e.* giving very similar values of the partial  
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44 objectives, differ considerably in the location and geometry of individual passages.

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46 The optimization algorithm was prepared with a view to the optimization of partial objectives.  
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48 Therefore, in order to solve the set optimization task of individual partial objectives, they  
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50 were defined as the inverses of the parameters being optimized. Additionally, appropriate  
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constant factors were introduced in order to ensure a comparable order of the values of individual partial objectives. The parameters under optimization were derived from numerical simulations comprising the field of temperature and stress in the blade.

As a result, in the Pareto sense of optimization, a group of solutions is obtained that cannot be compared (not being in any relation) to one another in the sense of the domination definition.

The solution, defined eventually as optimal, can be chosen from this set for example on the basis of other additional premises.

Because of too great a number of non-dominated solutions, in practice it is usually very difficult to find them all. Owing to the evolutionary algorithm, only a finite group of representatives of the Pareto front is found on the basis of the location of which its approximate shape can be determined.

In this work the Pareto approach was applied to solve the task with the three objectives discussed above. Additionally, similar calculations were conducted for two objectives *i.e.* the thermal one and the strength one, as factors which predominantly determine the durability and safe operation of components. Such a problem formulation allows a clearer presentation, in the graphic form, of the front of non-dominated solutions, which facilitates an analysis of the results obtained.

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Apart from the calculations to find the Pareto front, other optimization calculations can be made by means of the Weighted Single-Objective Method. In this approach optimization concerns the scalar function which is the weighted sum of all objectives. The multi-objective problem then comes down to the problem of single-objective optimization of the function expressed by the formula:

$$f = \sum_i Z_i w_i \left( \frac{X_i - X_i}{X_i} \right)^2, \quad X = [T_{\max}, s_{\max}] \quad (2)$$

1  
2 In the formula above, values  $X_i$  denote the target values of the parameters of the  
3  
4 objective function  $X$ , the weights of the individual factors are denoted as  $w$ , and  $Z$  is a  
5  
6 constant whose task is to match the values of the individual addends of sum (2) to each other.  
7  
8 The solution obtained in this way depends strongly on the values of the assumed weights, the  
9  
10 choice of which reflects the relative "importance" of individual objectives with relation to the  
11  
12 problem as a whole. The impact of individual components of the objective function on its  
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14 value can be controlled by proper selection of the weight factors  $w$ . The choice of weights is  
15  
16 usually made on the basis of a task analysis, and the minimum of function (2) is one of the  
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18 possible solutions on the Pareto front. Obviously, this approach does not provide any  
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20 information as to the location of the non-dominated solutions, which in turn does not allow  
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22 the researcher to fully assess the chance for compromise between partial objectives. On the  
23  
24 other hand, there are usually so many acceptable solutions that it is practically impossible to  
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26 provide their numerical determination or to select from them the non-dominated solutions.  
27  
28 Thus, it is necessary to reduce the multi-objective problem, and optimization by means of the  
29  
30 single-objective function is an instance of this. In the problem considered, the minimization of  
31  
32 function (2) will lead to a reduction in the maximum temperature of the blade ( $T_{max}$ ), and to a  
33  
34 minimization of relative stresses defined as follows:

$$s_{max} = \max \left( \frac{\sigma_{max}^1}{\sigma_{max}^{1ref}}, \frac{\sigma_{max}^2}{\sigma_{max}^{2ref}}, \frac{\sigma_{max}^3}{\sigma_{max}^{3ref}} \right) \quad (3)$$

35  
36 The maximum relative stress (3) is determined by the ratio of the maximum stress  
37  
38 component, for a given cooling option, to the same component obtained in the reference case.  
39  
40 If the value  $s_{max}$  is greater than 1, it means that the value of one of the stress components  
41  
42 exceeded the value of its corresponding component of the original solution.  
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46 Because, in its nature, the evolutionary algorithm seeks to maximize the value of the  
47  
48 adaptation function, in the problem considered, the following definition of this function was  
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50 used:  
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$$F = \frac{1}{\sqrt{f+1}}, \quad (4)$$

As already stated, due to such a formulation, the task is reduced to the problem of a single-objective optimization, the result of which is a single final solution.

### 5. Optimization procedure

The optimization procedure using both the model assumptions discussed above and the adopted methodology was implemented in the form of a numerical code whose task was to automate the entire computational process. The aim of the developed program was to integrate the evolutionary algorithm applied for the optimization with the module of the computational model construction (generation of the shape of the passages), and with the commercial numerical software, as a tool for the assessment of individual solutions. The diagram illustrating the operation of the developed optimization procedure is shown in Fig. 2.

Before the program is run, the basic parameters for its operation are defined, such as the number of the cooling passages, the size of the evolutionary algorithm population, the probability of mutation and crossover, and the constraints (the minimum and maximum size of the passage, the minimum thickness of the material between passages and between a passage and the blade wall). Then the initial population composed entirely of physically appropriate configurations of cooling systems is generated at random. The population individuals are coded with real numbers normalized to the range of [0:1] in a local coordinate system correlated with the blade under analysis. The details concerning this issue were discussed by Nowak and Wroblewski (2009). The information carried by the chromosome of an individual which relates to the cooling system configuration is subsequently decoded and used to build the computational model. It is at this stage that the profile geometry is read in, and the construction of the shape of passages begins with the use of Bezier curves. At the same time, the generated passage system is checked for compliance with the adopted constraints. Using the obtained passage shapes, the boundary conditions are

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2 formulated, the FEM grid is built, and the thermal and strength numerical calculations are run.  
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4 Each individual is subject to this process, and then the Pareto front for each generation or – in  
5  
6 the case of single-objective optimization – the ranking of individuals is determined. Next the  
7  
8 individuals undergo evolutionary processes and a new offspring population is formed. In this  
9  
10 way a single computational cycle (one generation) is completed. The process continues until  
11  
12 convergence is reached, which in this case consists either in no improvements made to the  
13  
14 solutions in 50 subsequent generations, or in filling the entire population with Pareto optimal  
15  
16 individuals. After convergence is reached, the individuals may be verified (temperature and  
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18 stress field) by means of more precise numerical models, *i.e.* models that cannot be used in  
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20 optimization directly, due to the computational cost.

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## 21 6. Computational model

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24 The test calculations connected with the optimization of the cooling system of a gas  
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26 turbine blade were conducted for profile C3X (Fig. 3) taken from the reference literature. The  
27  
28 choice was made due to the availability of experimental results concerning heat transfer on  
29  
30 the surface of the blade (Hylton *et al.*, 1983). On the basis of the experiments the thermal-  
31  
32 flow conditions were determined for the flow of both the hot gas and the coolant in the  
33  
34 passages, which in turn helped find the solution to the conjugate heat transfer task (CHT).  
35  
36 Hence, the boundary conditions, which were steady in the optimization process, were  
37  
38 formulated for the heat transfer on the surface of the profile. In the cooling passages the same  
39  
40 boundary conditions were determined on the basis of empirical formulas determined for the  
41  
42 flow through a smooth pipe (for a fully developed flow):

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$$43 \quad Nu = 0.023 Re^{0.8} Pr^{0.4}, \quad (5)$$

44  
45 and were designated for each passage separately. The formula makes it possible to assess, in a  
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47 simplified manner, the heat exchange conditions in a passage for the set flow parameters of  
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49 the coolant. According to reference literature, the dependence is perhaps not the most precise  
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one, but due to its simplicity it is widely used. It is also used by Hylton in his study which is the basis for the determination of the operation conditions for the analyzed blade. The conditions can be determined more precisely using Rayleigh flow, but this requires solving the temperature field iteratively in order to determine the heat flux absorbed by the coolant. On this basis, an approximate assessment of the change in the cooling agent parameters, and – consequently – in the boundary conditions, can be made. Another way is to use the CHT calculations. Both approaches entail lengthening the time needed to perform the calculations, and in the case of the CHT calculations the increase in the computational cost is huge.

Because the geometry of the passages differed significantly depending on their location in the blade and on the specific solution case, the hydraulic diameter of the passage was used in the calculations. To determine the flow in the passage, the following values were taken: total pressure  $p_{in} = 0.3 \text{ MPa}$  and total temperature  $T_{in} = 375 \text{ K}$  at the inlet, and static pressure at the outlet  $p_{out} = 0.275 \text{ MPa}$ . Furthermore, it was assumed that the cooling agent heats up during the flow through the passage ( $z$ ) in accordance with the dependence expressed as follows (Lienhard IV and Lienhard V, 2008):

$$T(z) = (T_{in} - T_{wall}) \exp\left(-\frac{h\pi d}{\dot{m}c_p} z\right) + T_{wall} \quad (6)$$

The observed increase in the coolant temperature reaches from several to a few dozen  $K$ , depending on the geometry of the passage.

In order to assess the impact of the boundary conditions and the numerical grid quality on the values of the optimized parameters, appropriate tests based on a randomly chosen p-optimal configuration were carried out. The test consisted in a thermal-strength simulation for:

- a 10% higher convective heat transfer coefficient in the passages.
- a 10% lower temperature of the passage wall  $T_{wall}$  – formula (6).

The absolute and percentage differences obtained from the test are presented in Table 1.

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It can be noticed that the inaccuracy of the estimate of the heat transfer coefficient at the level of 10% causes a change in the modelled maximum temperature at the level of approx. 1.5%. The change in the stress coefficient is similar. The difference in the stress coefficient value is caused predominantly by the change in the value of compressive stress which coincides with an opposite change in the tensile stress. If the obtained values of von Mises stress were compared, the change would be hardly noticed. The observed influence of the passage wall temperature on the maximum temperature and stress coefficient values was very small.

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For the optimization task specified above, appropriate thermal-strength calculations were conducted, which allowed a determination of individual partial objectives of the problem. The calculations were made with the use of the ANSYS software based on the Finite Element Method (FEM). The optimization algorithm was equipped with a module to prepare the FEM computational model in the form of a script, which allowed an automation of the whole computational process. Before the optimization process was started, tests were conducted to determine the level of discretization needed to solve thermal-strength tasks in a way that would make the solution independent of the numerical grid. The discretization was carried out with the use of hexagonal elements with a non-linear shape function, ensuring in this way a satisfactory solution standard, concerning in particular the sensitive stress field, for various configurations of the cooling system.

The fact that the evolutionary approach requires an analysis of very many alternative solutions (more than twenty thousand in this case) necessitated a parallelism of the calculations, especially the FEM analyses, which are the most time-consuming stage in the search for the optimal solution.

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The process of the analysis of thermal-strength states of individual configurations of the cooling system was composed of two stages. Firstly, the field temperature was modelled according to the thermal boundary conditions. Secondly, on this basis and with the set support

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2 conditions, the stress field was determined. The whole evaluation process for a single solution  
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4 lasted approx. 1.5 minutes. More than 75% of that time was consumed by structural  
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6 computations (threefold higher number of DOFs than for a thermal task, and a higher number  
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8 of data to be recorded and read from the disk). The time needed to obtain a solution by means  
9  
10 of eight parallel processes was 7–10 days. The computations were conducted using an  
11  
12 INTELi7 computer with 8GB RAM.

### 13 14 15 **7. Test calculations**

16  
17 Within this study a series of calculations was carried out in order to optimize the shape  
18  
19 and location of the passages of inner cooling of the C3X blade. As it was mentioned above,  
20  
21 the optimization was based on the Pareto approach with the use of two and three objectives.

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23 Two options of the cooling system were assumed, *i.e.* a 4- and a 5-passage one, and for both  
24  
25 options the p-optimal solutions were sought. The impact of the population size on the location  
26  
27 of the front of non-dominated solutions was also examined. For comparative reasons,  
28  
29 optimization calculations were also made with the weighted single-objective function (2) for  
30  
31 the 4- and 5-passage case.

32  
33 The optimization calculations that were conducted show that, in the case of the Pareto  
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35 approach, convergence was reached with a much smaller number of iterations for the two-  
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37 objective task than for the problem with three objectives. The calculations made for two  
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39 different population sizes (100 and 200 individuals) show that the difference is almost tenfold.  
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41 This seems to be justified as, taking into consideration the domination relation, the probability  
42  
43 of generating a solution better with respect to at least one objective increases with the increase  
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45 in the number of objectives. No significant difference was observed, however, in the  
46  
47 convergence history for the options with 4 and 5 passages (32 and 40 design variables);  
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49 nonetheless the case with 5 holes required a greater population. The criterion assumed for the  
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51 calculations to be stopped was the moment when the whole population was composed of non-  
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2 dominated individuals only. For the task with the weighted single-objective function the  
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4 calculations were stopped if no improvement in the solution was observed in 50 consecutive  
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6 generations. In this case, the calculations were made for a population consisting of 100  
7  
8 individuals, which resulted in a solution after the number of iterations approx. five times  
9  
10 smaller than in the same Pareto approach. It should be noted that a greater number of  
11  
12 iterations does not necessarily entail a higher computational cost. It turns out that the whole  
13  
14 number of the cooling system options analyzed in all the discussed approaches, for the same  
15  
16 size of the population of individuals, is comparable.

## 17 18 **8. Discussion of results**

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20 The object of comparison for the configurations which result from the optimization  
21  
22 process is the original cooling system, for which the results of the thermal-strength analysis  
23  
24 are shown in Fig. 4. On the left the distribution of temperature on the blade surface is  
25  
26 presented, on the right - the relative stress field.

27  
28 The optimization calculations led to a series of solutions, which are examples of the  
29  
30 cooling system configuration, depending on the procedure adopted for their evaluation.  
31  
32 Within the Pareto approach fronts of non-dominated solutions were obtained for populations  
33  
34 of different sizes. For the four-passage option, populations consisting of 60, 100 and 200  
35  
36 individuals were considered. As can be observed in Fig. 5, the front for the population with  
37  
38 the smallest number of individuals is definitely different from the location of the other two  
39  
40 fronts. A shift can be noticed here of practically the whole set of solutions towards both a  
41  
42 higher temperature and greater stress. From the remaining solutions it can be concluded that  
43  
44 the evolution process in this case stabilized at too high a level. It should be noted that the  
45  
46 population size for the worst set was only twice higher than the number of the design  
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48 variables, which hindered a proper exploration of the design space. Nevertheless, even in this  
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2 set it is possible to find the cooling system configurations which, with respect to both  
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4 objectives, are better than the reference option (Fig. 4).

5  
6 The solution fronts obtained for 100 and 200 individuals coincide to a great extent,  
7  
8 with the exception of the area of the lowest temperatures. With values of relative stress below  
9  
10 1, the two populations give very similar solutions, both in terms of the design variables space  
11  
12 (the cooling system configuration), and the solution space. Apart from the Pareto  
13  
14 optimization, another cooling system optimization was carried out with the use of the  
15  
16 weighted single-objective function (2) with equal weight coefficients ( $w_i = 0.5$ ), and for the  
17  
18 target temperature and relative stress values of 580K and 0.75 respectively. The course of the  
19  
20 process was plotted (Fig. 5). As can be observed, the solution obtained in this case is located  
21  
22 in the "worst" front. The maximum blade temperature obtained in the design approximated  
23  
24 the target value of (582K), but the relative stress value dropped only slightly below 1 and did  
25  
26 not reach the target level of 0.75. Comparing this solution to the p-optimal solutions obtained  
27  
28 in the first approach, it can be concluded that a further reduction in stress is impossible in the  
29  
30 imposed range of temperature. Fig. 6 presents the contour plots of the objective values for  
31  
32 selected non-dominated solutions and for the weighted single-objective function, according to  
33  
34 the denotations in Fig. 5. Option A presents the solution for function (2), whereas B - for the  
35  
36 closest to it, in the objective space, non-dominated solution (located on the "worst front").  
37  
38 Both configurations of the cooling system are similar to each other in terms of the location of  
39  
40 individual passages, and the greatest difference can be noticed in the shape and size of the  
41  
42 third passage. In option B it is much bigger, which contributes to a better cooling of the rear  
43  
44 part of the blade. In this option, the passage shape fits slightly better at the inlet of the blade,  
45  
46 which is characterized by a more uniform distribution of stress in this area. The next two  
47  
48 solution options (C and D) come from the front obtained for a population of 200 individuals.  
49  
50 Configuration C results in a stress level very similar to the ones in A and B, but with the

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2 maximum blade temperature lower by more than 10 K. This is due to the smaller thickness of  
3  
4 the wall at the inlet area of the blade, where the temperature is the highest. Another "hot" area  
5  
6 is located in the middle part on the suction side, where the laminar-turbulent transition in the  
7  
8 outer flow occurs. This area is cooled with a much bigger passage than in the other two cases.  
9  
10 Option D shows the solution with the lowest maximum value of relative stress. The topology  
11  
12 of this system is slightly different from option C, but these seemingly small differences allow  
13  
14 a dramatic reduction in the maximum level of relative stress from approx. 0.97 to 0.78.

15  
16 The same optimization process as the one discussed above for a four-passage cooling  
17  
18 system was also conducted for three objectives. In addition to temperature and stress, in this  
19  
20 case, the size of the coolant mass flow was taken into consideration. The optimization, based  
21  
22 on the result of previous analyses, was carried out for a population of 100 and 200  
23  
24 individuals. Analyzing the course of the process, it is possible to notice a much faster  
25  
26 convergence of the optimization algorithm in comparison to the calculations conducted for  
27  
28 two objectives. The reasons for this situation can be attributed to the fact that the probability  
29  
30 of finding (by means of evolutionary operations) an individual better with respect to at least  
31  
32 one objective increases with the increase in the number of objectives.

33  
34 Fig. 7 shows the fronts of p-optimal solutions of the three-objective task for a  
35  
36 population of 100 and 200 individuals. Analyzing the results, it is possible to notice that, in  
37  
38 comparison to the two-objective optimization, the cooling system configurations that are  
39  
40 obtained are characterized by higher stress. The reduction in the maximum temperature of the  
41  
42 blade is similar, but it is gained with much lower flows of the cooling agent. The reason for  
43  
44 such location of the front is the fact that the objectives that are affected by a greater number of  
45  
46 variables are minimized more slowly. It is easier to obtain passages of relatively small sizes  
47  
48 (carrying less cooling agent) and located close to the maximum temperature zones than to  
49  
50 ensure a low stress level. The temperature level is most affected by the location of the first  
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2 and second cooling passage and their distance from the blade edge, which depends on about 5  
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4 design variables per passage, *i.e.* maximum 10 variables in total. These are mainly points  
5  
6 which define an onset of a passage( $n_{1s}$ ) and appropriate coefficients that determine the blade  
7  
8 wall thickness between a passage and the external profile( $q_1, q_2, q_5, q_6$ ). The coolant mass  
9  
10 flow is determined, mainly, by the cross-sections of the first two passages, which again is  
11  
12 reflected by a similar number of parameters. In this case, the key role is played by variables  
13  
14  $n_{1s}$  and  $n_{2s}$  (or their mutual distance), which influence the chordwise length of a passage, and  
15  
16 coefficients  $q_1$  and  $q_2$  responsible for the passage size in the circumferential direction. In  
17  
18 comparison, the stress level can be determined by all 32 design variables, and by the relations  
19  
20 among them. The maximum stress values depend both on the local temperature field  
21  
22 determined by the location and size of the passages and on the shape of the passage itself  
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24 (fillet radii).

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26 It should be mentioned here that the location of the front did not change if populations  
27  
28 with a much higher number of individuals were used.

29  
30 In order to solve the problem discussed above, a two-step optimization was carried  
31  
32 out. The first phase consisted, as in the previous case, of two-objective optimization  
33  
34 (temperature and stress), and after convergence was obtained, the third objective was added  
35  
36 (mass flow). This of course required an introduction of new individuals into the population so  
37  
38 that the effect of solution space exploration could be achieved again. It was decided to expand  
39  
40 the final population by 20% of randomly generated individuals. In this way the algorithm  
41  
42 managed to find designs with a reduced coolant consumption. Obviously, the optimization  
43  
44 calculations last longer because of that, but it is possible to obtain a much wider range of p-  
45  
46 optimal solutions from which the final construction can then be selected, according to any  
47  
48 additional requirements. Fig. 8 presents the Pareto front obtained with the use of this  
49  
50 approach.

1 Analogous calculations were made for a blade with five cooling passages. With a view  
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3 to matching the proper size of the population to the increased number of design variables,  
4  
5 calculations were conducted with the use of the previously gained experience. It turned out  
6  
7 that the population that allowed obtaining the lowest location of the solution front (2  
8  
9 objectives) consisted of 120 individuals, *i.e.* by 20% more than before. The front of non-  
10  
11 dominated solutions which was the outcome of the optimization procedure is practically  
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13 established in the same area of the space of the objectives as an analogous front for the case  
14  
15 with four passages. The distribution of passages in the blade is also comparable. There is still  
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17 one passage that cools the nose of the blade, and some other, four in this case, passages of a  
18  
19 smaller cross-section whose task is to reduce the temperature in the middle and rear part of  
20  
21 the component. Diminished passages can be the strong point of the five-hole design because  
22  
23 due to the smaller volume of individual holes the rigidity of the blade increases, which can  
24  
25 substantially affect vibrations and fatigue of the component. Fig. 9 presents the front of non-  
26  
27 dominated solutions for the two-objective task, and Fig. 10 shows the selected sample  
28  
29 solution of the design task for which the lowest possible level of relative stress was obtained.  
30  
31 In this solution, the temperature was reduced by 45K compared to the reference solution,  
32  
33 which is accompanied by a fall in maximum stress by approx. 15%. The three-objective task  
34  
35 was dealt with in the same way as the problem with four passages, *i.e.* with the use of the two-  
36  
37 step optimization procedure. The first phase was conducted on a population of 120  
38  
39 individuals; in the second phase the number of individuals was increased by 30. In this way,  
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41 the obtained front was expanded by constructions characterized by a reduced demand for the  
42  
43 cooling agent, but with higher values of the remaining two objectives.  
44

## 45 9. Conclusion

46 The article presents a methodology concerning the optimization of the shape and  
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48 location of passages cooling the blade of a gas turbine. To model the shape, Bezier curves  
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2 which form a smooth, closed contour of the passage cross-section were used. In order to allow  
3 proper shape "flexibility", it was decided to use four Bezier segments to model a single  
4 passage. Additionally, in order to match the passage shape to the local geometry of the blade,  
5 a "shape copy" technique was proposed for two opposite Bezier segments extending along the  
6 profile. It consisted in copying and scaling the shape of a fragment of the blade contour  
7 inside. The two segments which were so built were closed with another two curves, obtaining  
8 in this way a closed contour. This way of modelling required the determination of 8 variables  
9 which determined the location and shape of the passage.  
10  
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12 For the cooling system modelled in this way, multi-objective optimization calculations  
13 were conducted for cases with two and three objectives. The aim of the calculations was to  
14 obtain Pareto optimal cooling system structures evaluated on the basis of the maximum blade  
15 temperature, maximum stress and the coolant mass flow. The task was solved for a cooling  
16 system composed of four and five passages, which gave 32- and 40-dimensional design space,  
17 respectively. Observations of the impact of the population size on the standard of the solution  
18 were made, and p-optimal solutions were compared to the solution obtained for the weighted  
19 single-objective function. The impact of individual objectives on the level and the pace of the  
20 convergence of the task were also observed. In the presented results a premature convergence  
21 of solutions for too small populations can be noticed. Hence, a need arises to conduct earlier  
22 research concerning the population size for a given task. It was noticed that the objectives of  
23 temperature and the mass flow, due to the dependence on a small number of design variables,  
24 have a prevailing significance in the optimization process, as opposed to the stress objective.  
25 Because the stress level is in principle determined by all design variables, the fronts of non-  
26 dominated solutions obtained for the 3-objective task are located within ranges of relatively  
27 high stress which is much more likely to be obtained by means of stochastic methods. The  
28 proposed two-step optimization procedure can be a solution to this situation. It consists in  
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2 obtaining solution fronts for two objectives (the thermal and stress objective), and then  
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4 initiating a task that allows for the mass flow objective. The second phase is carried out on an  
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6 increased population of individuals which is composed of the individuals from the Pareto  
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8 front obtained in the first phase of the procedure, and a fixed number of newly generated  
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10 individuals. Such an approach extends the current front towards solutions characterized by a  
11  
12 lower flow of the cooling agent.

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14 All the solutions obtained in this study were compared to the reference case with  
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16 respect to the assumed optimization objectives. The optimization resulted in such structures of  
17  
18 the cooling system that made it possible to significantly reduce both the level of the blade  
19  
20 material temperature and of the stress. This is of course achieved at the expense of a higher  
21  
22 demand for the coolant. The reduction in temperature reaches as much as 50K, with an almost  
23  
24 25% fall in stress at the same time. A cooling system like this allows an increase in the  
25  
26 temperature at the inlet of the turbine, which in turn will be reflected in the improved  
27  
28 efficiency of the whole power generation system.

### 29 **Acknowledgments**

30 The authors would like to thank the Ministry of Science and Higher Education,  
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32 Poland, for the financial assistance with grant no. N N513396036.

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2 Fig1. Passage shape modelling with Bezier spline

3 Fig2. [Optimization process flow chart](#)

4 Fig3. C3X blade

5 Fig4. Temperature (left) and relative stress (right) distribution for the original cooling system

6 Fig5. Pareto fronts for different population sizes

7 Fig6. Selected cooling system design

8 Fig7. Pareto fronts for the three-objective task

9 Fig8. Pareto front for two-step optimization

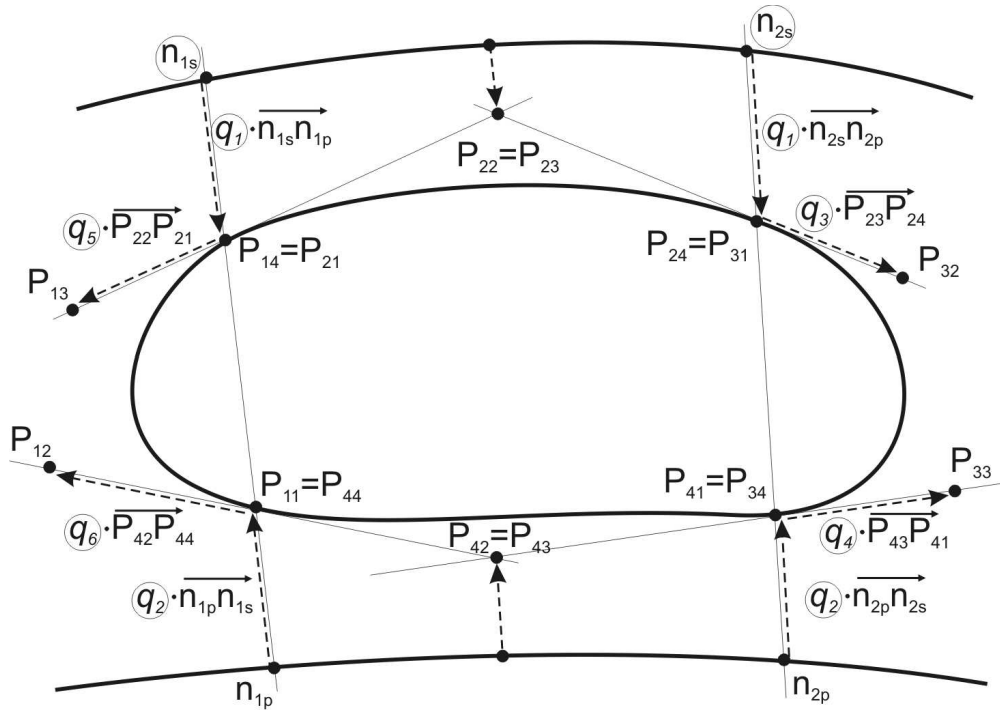
10 Fig9. Pareto front for five passage case

11 Fig10. Selected design of five passage cooling system - temperature and relative stress  
12 distributions.

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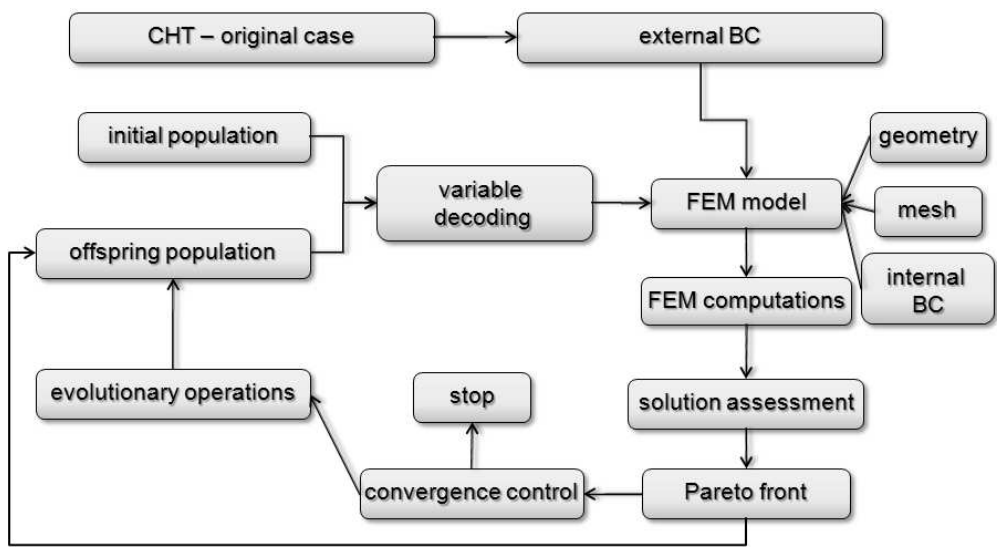
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Passage shape modelling with Bezier splines.  
124x87mm (300 x 300 DPI)

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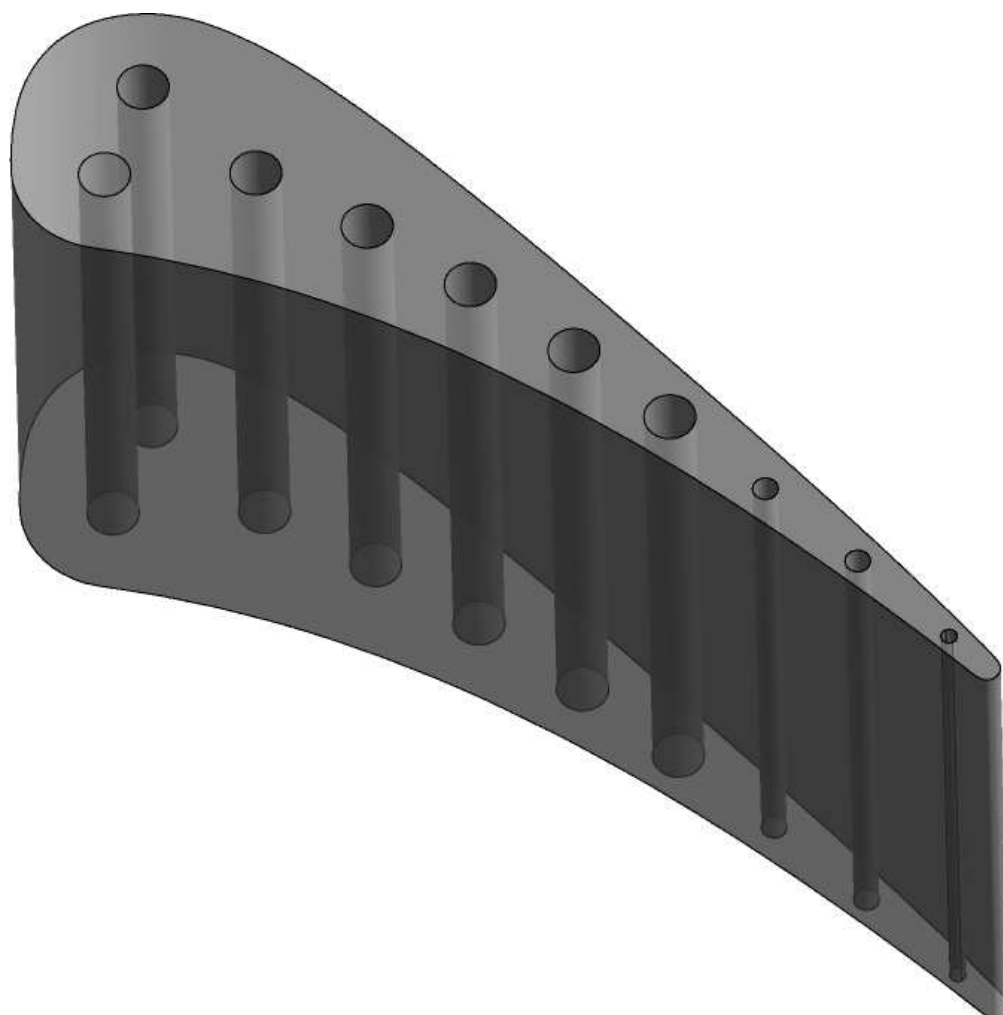
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Optimization process flow chart  
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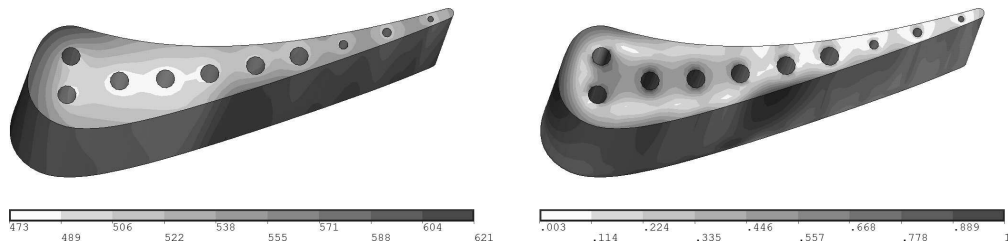


C3X blade.  
237x238mm (72 x 72 DPI)

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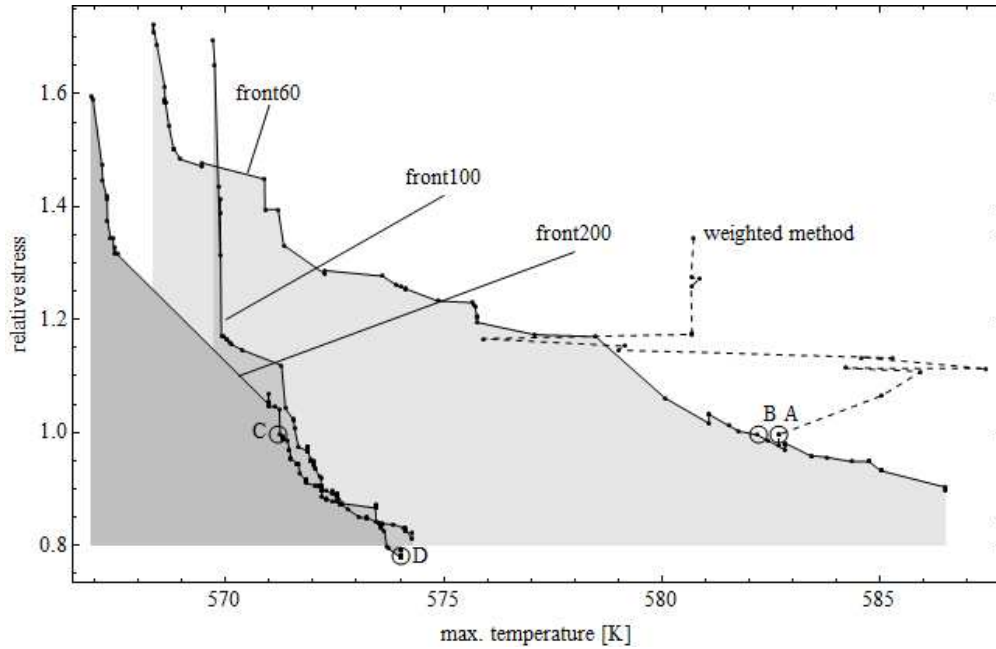


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Temperature (left) and relative stress (right) distribution for the original cooling system.  
177x41mm (300 x 300 DPI)

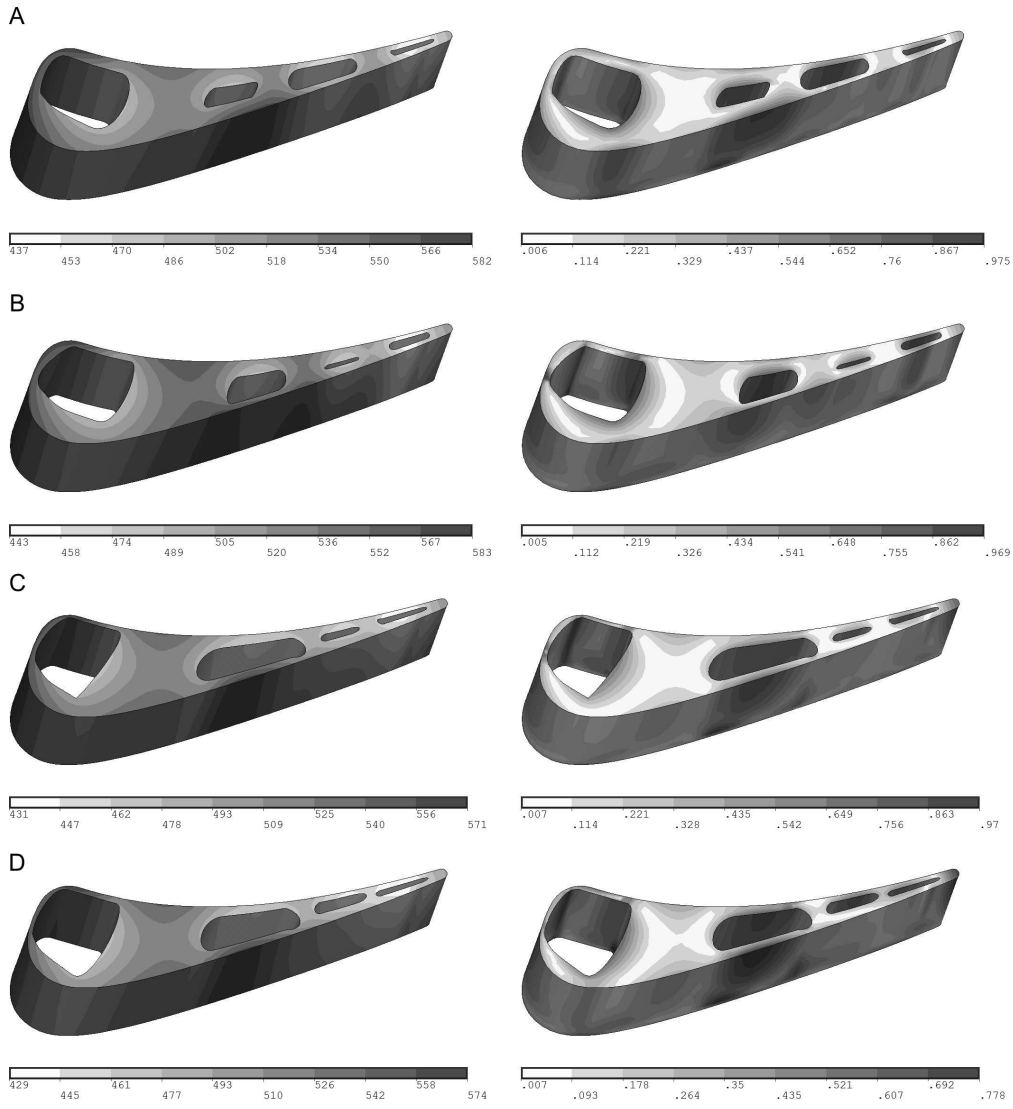
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Pareto fronts for different population sizes.  
226x145mm (72 x 72 DPI)

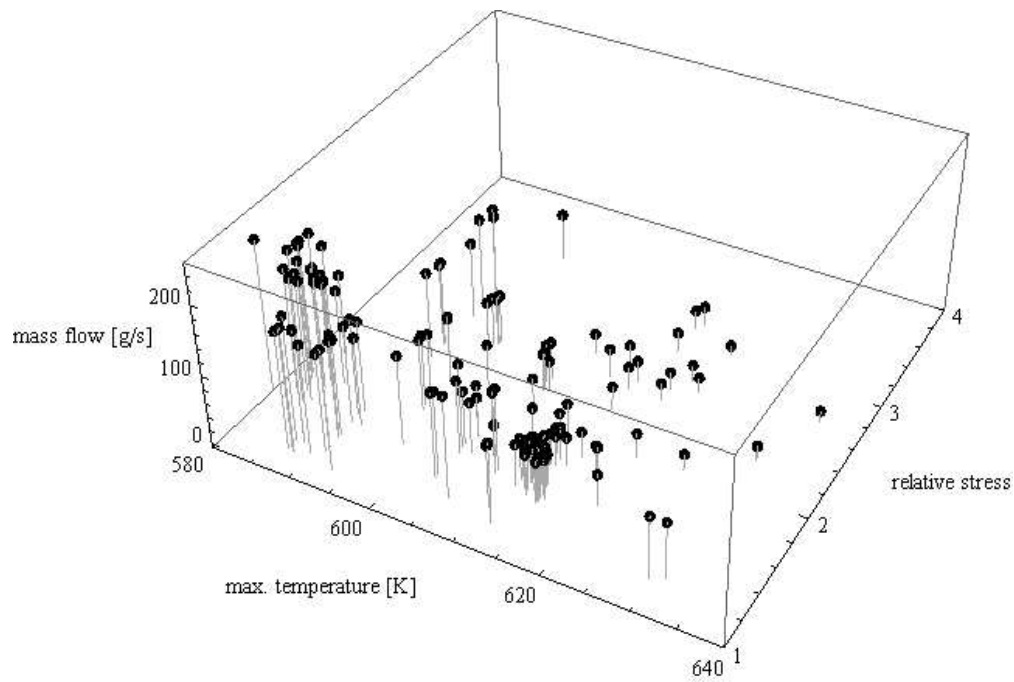
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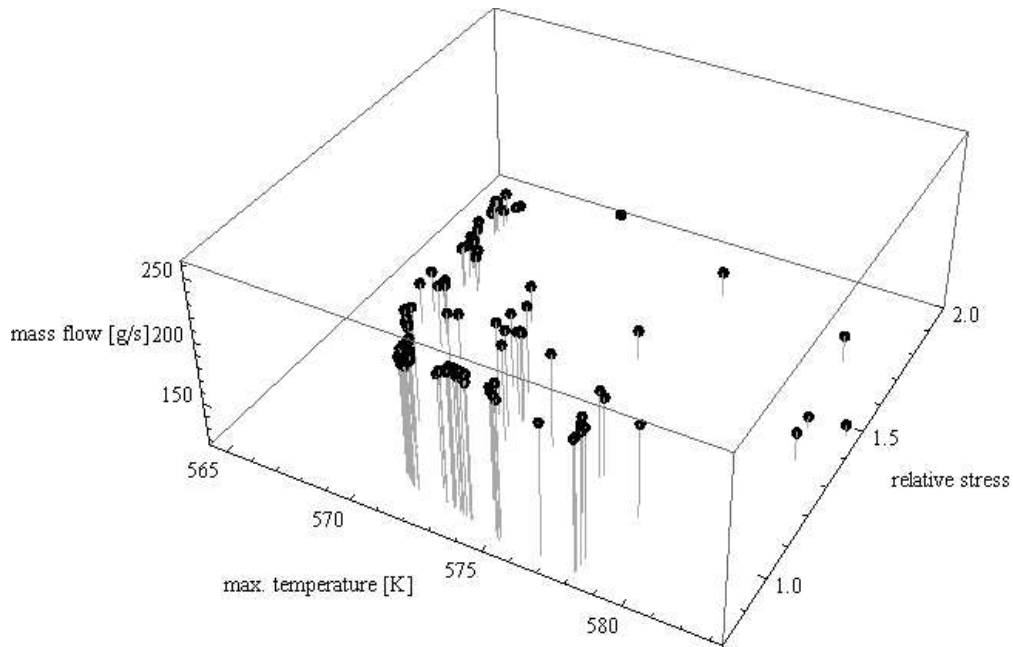
Selected cooling system designs.  
178x198mm (300 x 300 DPI)





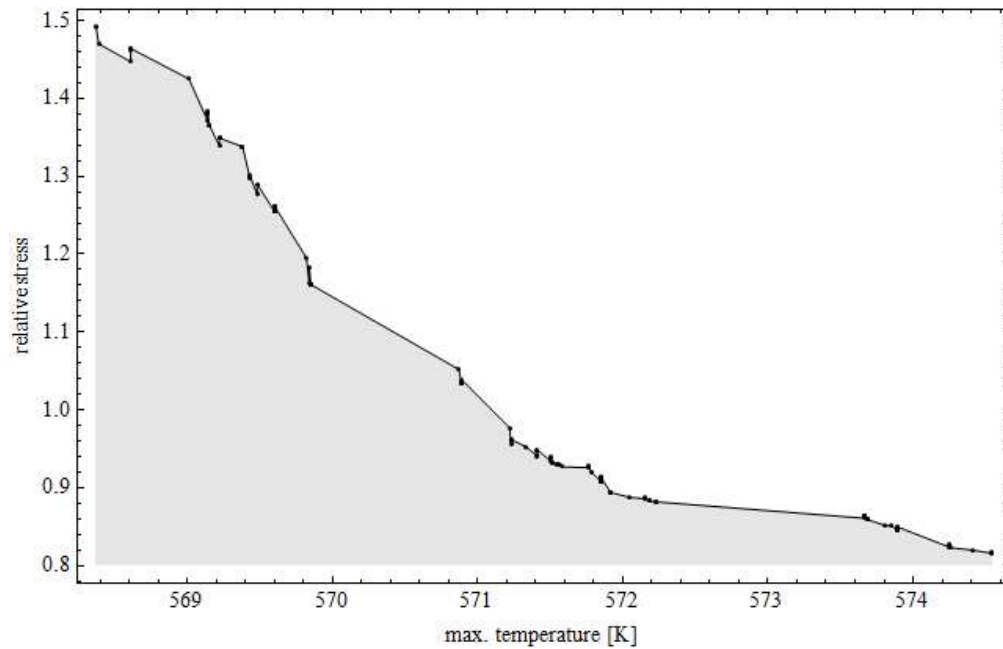
Pareto fronts for the three-objective task.  
227x152mm (72 x 72 DPI)

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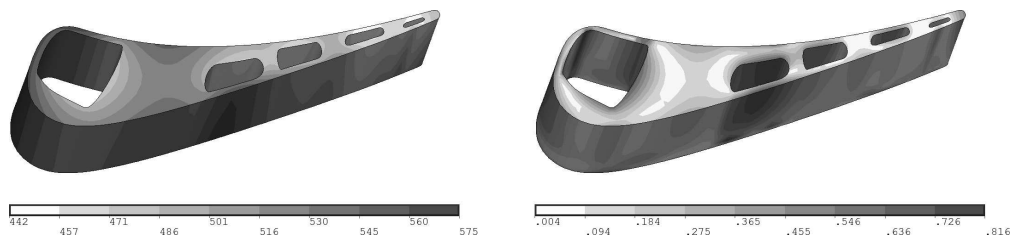
Pareto front for two-step optimization.  
228x146mm (72 x 72 DPI)

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Pareto front for five passage case.  
225x144mm (72 x 72 DPI)

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Selected design of five passage cooling system - temperature and relative stress distributions.  
183x41mm (300 x 300 DPI)

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		value	% change	value	% change
T <sub>max</sub> , K	573.7	565.2	1.5	572.9	0.3
S <sub>max</sub>	0.866	0.883	2	0.868	0.2

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