Construction optimization of hydrodynamic torque converter with application of genetic algorithm

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This paper describes multi-objective construction optimization of hydrodynamic torque converter with the application of a genetic algorithm. The main optimization criteria were: torque ratio, efficiency, permeability and a range of high efficiencies. Overall 16 variables were selected as main optimized parameters. Among them were: active diameter, parameters of meridional cross section, blade angles on core and shell. Value ranges of these variables were obtained from the analysis of constructed prototypes. Mathematical model based on multiple streams was applied. Sample calculations were provided for hydrodynamic torque converter type PH 410. The results of these calculations provided a set of suboptimal parameters that were utilized as a basis for further consideration. In addition, influence of range limitations of optimized parameters into optimization results was analyzed. The influence varies significantly.

Keywords: Construction optimization, hydrodynamic torque converter, genetic algorithm

1. Introduction

Hydrodynamic torque converters (HTC) are widely used in vehicle power transmission systems. HTC construction is simple, reliable and long lasting. Major disadvantages of HTC are low efficiency, necessity of delivering working fluid and relatively low torque ratio. Due to low torque ratio the HTC works together with a mechanical transmission creating a hydrodynamic power transmission system. The main advantage of hydrodynamic power transmission system application is its smooth, quiet and long lasting reliable performance.

In order to select best suitable construction of HTC an application of mathematical modelling to construction optimization calculations is necessary. Mathematical models based on average stream theory are still applied. In order to increase modelling accuracy additional parameters such as working fluid temperature [9], or considering the working fluid flow through as a set of individual streams and diligent parameter estimation for the mathematical model [8] are introduced. HTC model estimation calculations apply stochastic methods. In order to perform proper estimation empirical testing of the considered HTC is required.
2. Construction optimization of the hydrodynamic torque converter

Construction optimization of the particular HTC to be included in the analyzed hydrodynamic power transmission system relies on optimal selection of values of pre-selected parameters of HTC working area.

2.1. Hydrodynamic torque converter quality indicators

In order to determine quality of HTC working in the hydrodynamic power transmission system, HTC quality indicators were introduced [8, 15]. These indicators evaluate steady-state characteristic, implementation properties, production and HTC ability to fulfill traction requirements of a vehicle where it is applied. Construction optimization uses quality indicators sorted into four groups:

- related to load type,
- related to power transfer type,
- related to condition of engine operation,
- economical.

Method of selecting parameters to define HTC quality indicators are shown on Figure 1. HTC loading properties are characterized by torque factors in pump impeller \( \lambda_{M,1} \) and turbine impeller \( \lambda_{M,2} \):

\[
\lambda_{M,1} = \frac{M_1}{\rho \omega_1 \omega_1 D^5}; \quad \lambda_{M,2} = \frac{M_2}{\rho \omega_1 \omega_1 D^5},
\]

where:

- \( M_1, M_2 \) – torque of input and output shaft, respectively,
- \( \omega_1, \omega_1 \) – angular speed of input and output shaft, respectively,
- \( \rho \) – density of working fluid,
- \( D \) – HTC active diameter.

![Fig. 1. Method of defining HTC quality indicators \( i_{do}, d_{75} \) and \( \eta_{max} \)](image-url)
HTC power transferring properties are characterized by torque ratio \( i_d = M_2/M_1 \) defined for this purpose as:

\[
i_d = \lambda_{M,1} / \lambda_{M,2},
\]

(2)

and value of torque ratio \( i_{do} \) for \( i_k = \omega_2/\omega_1 = 0 \).

Conditions of engine operation are characterized by permeability \( p \):

\[
p = \lambda_{M,1,max} / \lambda_{M,1}',
\]

(3)

where:

\( \lambda_{M,1,max} \) – maximum value of torque factor,

\( \lambda_{M,1}' \) – torque factor for \( i_d = 1 \).

HTC economical properties are characterized by the range of high efficiencies \( d_{75} \):

\[
d_{75} = \frac{i_{k,75,max}}{i_{k,75,min}},
\]

(4)

and by maximum efficiency \( \eta_{max} \) defined by equation \( \eta_{max} = (i_k i_d)_{max} \).

The HTC quality indicators applied during optimization proceedings depend on:

- geometric parameters of HTC working area,
- working fluid selection,
- construction of other HTC components.

During steady-state motion of hydrodynamic power transmission system HTC quality indicators are constant.

2.2. Optimization method

Selection of HTC optimization method depends on mathematical representation of this optimization problem. Due to:

- non-linearity and sophisticated form of applied HTC mathematical models,
- number of limitations with various magnitude and form,
- number of optimized parameters,

up to now HTC optimization utilizes primarily stochastic methods such as Monte Carlo or combinatorial and heuristic method Linja [1, 8, 11, 15].

2.3. Optimization criteria

Construction optimization contains three groups of optimization criteria as follows:

- criteria of highest rigidity,
- criteria of constant strength,
- criteria of minimum cost.
Rigidity and strength of impellers is determined by construction technology. Typical construction technologies provide blades and walls of core and shell with thickness from 3 to 4 mm for cast impellers and from 0.8 to 1.2 mm for impellers made from pressed steel metal sheets. Therefore the most important HTC design criterion is minimization of cost. This criterion is tied to vehicular performance where the hydrodynamic power transmission system is applied [8]. Production cost and transportation of worked-on media were taken as a construction optimization criteria of HTC applied to heavy duty work machinery [15]. These criteria were defined as a maximization of an average efficiency of each working cycle in work [15]. Other works such as [10] recommend using range of economical HTC performance – $d_{75}$, this criterion should lead to maximum performance.

Also in practice as optimization criteria the following quality indicators are used [15]:
- HTC efficiency – $\eta_{\text{max}}$,
- torque ratio for zero speed ratio – $i_{\text{d0}}$,
- permeability – $p$,
- HTC range of high efficiencies – $d_{75}$.

These indicators also should reach the highest possible values.

2.4. Optimized parameters

Optimized parameters required during construction optimization of HTC should be selected from a set of all HTC parameters. All selected parameters have to be present in the applied optimization mathematical model. During HTC optimization geometrical parameters of working area are primarily considered such as: HTC working area meridional cross section shape [5, 12, 18] number of blades [16], profile of stator blades [14], and additional mass moments of inertia and rigidity of impellers shafts [17].

Stochastic calculation methods tend to significantly increase the number of required iterations with increased number of variables. Therefore variables with the most significant influence on optimization criteria should be selected to become the optimized parameters. Work [15] recommends selecting 6 optimized parameters for construction optimization of HTC such as blade angles on average line on inlet and exit of impellers – $\beta_{ij}$. Works such as [2] selected the following 10 parameters as optimized parameters:
- HTC active diameter $D$,
- 6 mean path blade angles,
- 3 dimensionless coefficients that are included in mathematical description of geometrical working area shape.

2.5. Optimization model

The mathematical model of hydrodynamic torque converter applied to optimization should be [8]: simple, accurate, and it should allow estimation of model parameters. Such model is called multi-stream model and is described in chapters 2.51 and 2.52.
2.5.1. Multi-stream model assumptions

The multi-stream model designated for optimization was developed based on the following assumptions:
- entire through flow in HTC working area consists of \( n_o \) independent streams,
- a torque carried by HTC is equal to a sum of all streams torques carried by each individual stream,
- the contribution of each individual stream to carry out the torque differs and depends on assumed torque function \( y = f(x) \),
- each individual stream is described by a single-dimensional average stream model [8, 9, 13, 15],
- the result of the modelling of the entire through flow in HTC working area consists of the sum of the flow results for each individual stream included in the entire through flow in HTC working area.

Based on the analysis of actual velocity ranges in the HTC working area [2, 4] it was assumed that the torque function \( y = f(x) \) is sloping upward, is measurable, differentiable, and continuous in the range of \( 0 < x \leq 1 \) and that the torque function is characterized by values of three constant coefficients \( a, b, c \) obtained from the assumed range of change. The independent variable \( x \) in the torque function is a consecutive number \( n \) for each corresponding stream divided by the number of all streams in the considered through flow \( n_o \) \((0 < x \leq 1)\) but the contribution factor of the torque carrying through \( y \) in the range of \( (0 \leq y \leq 1) \) is taken as the dependent variable. Usually values of torque calculated with the average stream model are smaller than the values obtained from empirical measurements. This fact is considered as a major disadvantage of the average stream model [8–9, 13] therefore these parameters are multiplied by a constant \( z \) for every stream \((z > 1)\).

2.5.2. Model equations

The main purpose of the model is a calculation of the non-dimensional steady-state characteristic of HTC for pre-selected values of speed ratio \( i_k \) with utilization of numerical methods, therefore it is considered to be as a discrete numerical model. The model equations are as follows:

\[
i_d(i_k) = \frac{M_2}{M_1}, \quad \lambda(i_k) = \frac{M_1}{\rho D^3 \omega_1^2}, \quad \eta(i_k) = i_d i_k^2,
\]

where:

\[
M_1(i_k) = z \sum_{n=1}^{n_o} y_n M_{1,n}, \quad M_2(i_k) = z \sum_{n=1}^{n_o} y_n M_{2,n},
\]

\[
M_{1,n} = \rho k_{12/32,n} Q^2 + \rho r_{12,n}^2 \omega_1 Q,
\]
\begin{align*}
M_{2,n} &= \rho k_{12,22,n} Q^2 + \rho r_{12,n}^2 \omega_1 Q + \rho r_{22,n}^2 \omega_2 Q, \\
a_{1,n} \omega_1^2 + a_{2,n} \omega_2^2 + a_{3,n} Q^2 + a_{4,n} \omega_1 Q + a_{5,n} \omega_2 Q &= 0
\end{align*}

and

\begin{align*}
k_{a/b} &= \frac{r_a}{F_m} \text{ctg } \beta_a - \frac{r_b}{F_m} \text{ctg } \beta_b, \\
a_{1,n} &= \frac{1}{2} \left( (2r_{12,n}^2 - r_{11,n}^2 - r_{12,n}^2) \right), \\
a_{2,n} &= \frac{1}{2} \left( (2r_{22,n}^2 - r_{21,n}^2 - r_{22,n}^2) \right), \\
a_{3,n} &= -\frac{1}{2} \left( \frac{1}{r_{11,n}^2} k_{32/11,n}^2 + \frac{1}{r_{21,n}^2} k_{12/21,n}^2 + \frac{1}{r_{31,n}^2} k_{22/31,n}^2 \right) - \frac{\psi}{F_{m,n}} \left( \text{ctg}^2 \beta_{12,n} + \text{ctg}^2 \beta_{22,n} + \text{ctg}^2 \beta_{32,n} + 3 \right), \\
a_{4,n} &= k_{12/32,n} + k_{32/11,n} - \frac{r_{12,n}^2}{r_{21,n}^2} k_{12/21,n}, \\
a_{5,n} &= -k_{12/22,n} - k_{12/21,n} + \frac{r_{22,n}^2}{r_{31,n}^2} k_{22/31,n}, \\
F_{m,n} &= \frac{\pi (r_{gw}^2 - r_{gw})}{n_o},
\end{align*}

where \( i \) is impeller number (\( i = 1 \) – impeller of the pump, \( i = 2 \) – impeller of the turbine, \( i = 3 \) – impeller of the stator), \( j \) is inlet or exit of impeller (\( j = 1 \) inlet, \( j = 2 \) exit),

\begin{align*}
r_{11,n} &= \sqrt{\frac{n}{n_o} r_{dz}^2 + \left( 1 - \frac{n}{n_o} \right) r_{dw}^2}, \\
r_{12,n} &= \sqrt{\frac{n}{n_o} r_{gw}^2 + \left( 1 - \frac{n}{n_o} \right) r_{dz}^2}, \\
r_{12,n} &= \sqrt{\frac{n}{n_o} r_{gw}^2 + \left( 1 - \frac{n}{n_o} \right) r_{gw}^2},
\end{align*}

where \( n \) changes from 0 to \( n_o \) and \( \overline{r}_{1,j,n} = \sqrt{\frac{r_{1,j,n}^2 + r_{1,j,n1}^2}{2}} \), where \( n \) changes from 1 to \( n_o \) determining a stream number.

\begin{align*}
\beta_{ij,n} &= \frac{(\beta_{gz} - \beta_{gw})(\overline{r}_{ij,n} - r_w)}{r_z - r_w},
\end{align*}

where: for the inlet \( r_w = r_{gw}, r_z = r_{gz} \), and for the outlet \( r_w = r_{dw}, r_z = r_{dz} \).
Remaining radii of the mean path streams were obtained as follows:
- for impeller of the turbine – the inlet radius equal to the exit radius of the pump impeller,
- for impeller of the stator – the inlet and the exit radius equal to the radius of the inlet of the pump impeller.

The radii determining impellers dimensions are shown in Figure 2.

Fig. 2. Proposed method of impellers radii marking

The following were provided as the input data to the model:
- parameters of HTC operation point – $i_k$ and $\omega_1$,
- model parameters: a number of speed ratio values $k_o$, a number of streams $n_o$, value of flow losses factor $\psi$, an increasing torque factor $z$,
- geometric dimensions of HTC working area – $D$, $r_{gz} = D/2$, $r_{gw}$, $r_{dz}$, $r_{dw}$, $\beta_{ij,z}$, $\beta_{ij,w}$,
- torque function $y = f(x)$ and its parameters: $a$, $b$, $c$.

The calculated results are: torques obtained on HTC inlet and exit shafts that allow obtaining non-dimensional steady-state characteristic of HTC (acc. to formulae (6)).

3. Construction optimization of the pre-selected hydrodynamic torque converter

Construction optimization was performed for HTC type PH 410. It is a HTC containing three impellers: pump, turbine, stator, Figure 2, with active diameter $D = 0.41$ m. Basic data pertaining to geometry of working area within this HTC are shown in Table 1.
Table 1. HTC type PH 410 data; $D$, $r$ [m], $\beta$ [°]

<table>
<thead>
<tr>
<th>$\beta_{11w}$</th>
<th>$\beta_{11z}$</th>
<th>$\beta_{12w}$</th>
<th>$\beta_{12z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td>94</td>
<td>133</td>
<td>131</td>
</tr>
<tr>
<td>$\beta_{21w}$</td>
<td>$\beta_{21z}$</td>
<td>$\beta_{22w}$</td>
<td>$\beta_{22z}$</td>
</tr>
<tr>
<td>33</td>
<td>30</td>
<td>156</td>
<td>149</td>
</tr>
<tr>
<td>$\beta_{31w}$</td>
<td>$\beta_{31z}$</td>
<td>$\beta_{32w}$</td>
<td>$\beta_{32z}$</td>
</tr>
<tr>
<td>74</td>
<td>85</td>
<td>20</td>
<td>23</td>
</tr>
</tbody>
</table>

3.1. Estimation of the model parameters

The parameter estimation calculations of the multi-stream HTC type PH 410 model was performed through comparison of empirical measurement data with the results obtained from the model. As an accuracy criterion the average relative error of modelling points from the non-dimensional steady-state characteristic of HTC was considered [8]. This criterion, calculated for all considered values of $i_k$ should obtain minimal values.

3.1.1. Empirical analysis and measurements

In order to estimate model parameters the empirical analysis and measurements were performed on the special testing rig that allowed loading the HTC with various torque continuously controlled under different rotational velocities of inlet and exit shafts. The analysis was performed under constant angular velocity of the inlet shaft equal to $\omega_1 = 210$ rad/s. The measured parameters were values of speed ratio $i_k$ within a range 0 to 1. Twenty four measurement points were taken ($k_o = 24$). For each measurement point a measurement of angular velocity on exit and torque on inlet and exit shaft were taken. Based on this measurement an empirical non-dimensional steady-state characteristic of HTC type PH 410 was created.

3.1.2. Estimating calculations

For estimation calculations the following were selected: a torque function in the form of $y = |a/(b + cx^3)|$, $a$, $b$, $c$ parameters: $z$, $\psi$ and a number of streams $n_o$. Values of the model parameters obtained based on calculations are shown in Table 2. Figure 3 shows a torque function curve.

Table 2. Parameter values obtained from estimation calculations

<table>
<thead>
<tr>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$\psi$</th>
<th>$z$</th>
<th>$n_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.43792766</td>
<td>1.09677419</td>
<td>1.99902248</td>
<td>0.39970674</td>
<td>2.74193548</td>
<td>30</td>
</tr>
</tbody>
</table>

3.2. Optimization procedure

The performed construction optimization of HTC type PH 410 was multi-objective. One optimization criteria was selected as the main one, the rest was converted to limits. The following main criteria were selected for the optimization quality of HTC:

- value of torque ratio $i_{do}$ for $i_k = 0$, 

- HTC permeability – \( p \),
- HTC range of high efficiencies – \( d_{75} \).

A multi-stream model was selected as a mathematical representation.

Fig. 3. Torque function curve \( y = \frac{a}{b + cx^3} \) with values of \( a, b, c \) per Table 2:
1 – curve after recalculation of function range to \( 0 \leq y_n \leq 1 \), 2 – function curve after multiplying by \( z \)

Among many parameters the following variables were selected as optimized parameters:
- HTC active diameter – \( D \),
- dimensionless parameters describing meridional cross section of HTC [8], Figure 2:

\[
\rho_1 = \frac{2r_1}{D}, \quad \rho_2 = \frac{2r_2}{D}, \quad \chi = \frac{2a}{D}, \tag{7}
\]

- blade angles on core and shell of HTC impellers (on core \( \beta_{ijw} \) and on shell \( \beta_{ijz} \), 12 parameters).

Overall 16 parameters were selected as optimized parameters. Ranges of each optimized parameter values assumed based on the parameter values obtained from the actual constructions of HTC [6] as shown in Table 3.

<table>
<thead>
<tr>
<th>( D ) [m]</th>
<th>( \rho_1 )</th>
<th>( \rho_2 )</th>
<th>( \chi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38 ( \geq D \geq 0.44 )</td>
<td>0.93 ( \geq \rho_1 \geq 0.945 )</td>
<td>0.547 ( \geq \rho_2 \geq 0.626 )</td>
<td>0.15 ( \geq \chi \geq 0.18 )</td>
</tr>
<tr>
<td>90 ( \geq \beta_{11w} \geq 130 )</td>
<td>90 ( \geq \beta_{11z} \geq 130 )</td>
<td>75 ( \geq \beta_{12w} \geq 150 )</td>
<td>75 ( \geq \beta_{12z} \geq 150 )</td>
</tr>
<tr>
<td>30 ( \geq \beta_{21w} \geq 75 )</td>
<td>30 ( \geq \beta_{21z} \geq 75 )</td>
<td>129 ( \geq \beta_{22w} \geq 160 )</td>
<td>129 ( \geq \beta_{22z} \geq 160 )</td>
</tr>
<tr>
<td>70 ( \geq \beta_{31w} \geq 140 )</td>
<td>70 ( \geq \beta_{31z} \geq 140 )</td>
<td>20 ( \geq \beta_{32w} \geq 50 )</td>
<td>20 ( \geq \beta_{32z} \geq 50 )</td>
</tr>
</tbody>
</table>
A simple genetic algorithm method was applied to optimization. The genetic algorithm is based on the natural process of selection. Genetic selection occurring in nature is mathematically modelled. Random selection is applied to find the minimum value of quality criteria. Crossing over parts of the coded strings, coding of solution range, multiplication of code strings and generation of pseudorandom numbers are applied in these models with using computer programming. In order to apply this method to parameter estimation, rescaling to range of 0 to 1 has to be performed. The parameters are binary coded with the resolution of ten binary places. The fitness function is defined as converging to the minimum. Different methods are used to obtain the optimal parameter selection and various probabilities of crossing and mutation are given. As a result a set of parameters providing minimum quality criteria value are obtained. The genetic algorithm parameter values applied during calculations are shown in Table 4.

Table 4. Genetic algorithm parameters recommended for further calculations

<table>
<thead>
<tr>
<th>Initial random value</th>
<th>Crossover probability</th>
<th>Mutation probability</th>
<th>Population size</th>
<th>Number of generations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>0.9</td>
<td>0.01</td>
<td>100</td>
<td>5000</td>
</tr>
</tbody>
</table>

In order to limit involvement inside of the genetic algorithm structure it was assumed that the fitness function value is decreased through its division by a constant $s$ whenever the required conditions by optimization criteria modified to limits are not met. The decrease of the fitness function value creates significantly increased probability of the elimination of such set of parameters from the optimization calculations. Since three criteria are converted to limits the fitness function is divided by $s^3$ in the worst case scenario. Based on the initial calculations the value $s = 10$ was assumed.

3.3. Optimization calculations for hydrodynamic torque converter

The main goal of optimization calculations is to find a set of values of the optimized parameters (16 selected parameters of HTC), where the main criteria obtains maximum and the criteria converted into limits fulfil the assumed limits at the same time. Beside calculations of the optimized parameters a numerical analysis of the limit influence and the range of the optimized parameters values on the results of the optimization were performed. During this consideration the HTC maximum efficiency $\eta_{\text{max}}$ was added as an additional criterion.

3.3.1. Calculation of a set of values of the optimized parameters

During the construction of the actual HTC the limits are determined by the constructor based on the technical requirements. In calculations of criteria converted into limits the assumed range of limits was determined based on construction recommendations [8, 15]. The limit ranges are shown in Table 5.
Table 5. The main criteria and the criteria converted into limits during HTC optimization

<table>
<thead>
<tr>
<th>No.</th>
<th>Main criteria</th>
<th>The optimal value obtained</th>
<th>Criteria converted into the limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$i_{do}$</td>
<td>Maximum</td>
<td>$d_{75} \geq 1.8; p \geq 1.3$</td>
</tr>
<tr>
<td>2</td>
<td>$d_{75}$</td>
<td></td>
<td>$i_{do} \geq 2; p \geq 1.3$</td>
</tr>
<tr>
<td>3</td>
<td>$p$</td>
<td></td>
<td>$i_{do} \geq 2; d_{75} \geq 1.8$</td>
</tr>
</tbody>
</table>

Calculations were performed based on custom computer programs written in Turbo Pascal high level programming language. The obtained results of maximal values of main criteria, values of limits and values of optimized parameters are shown in Table 6.

Table 6. Values of the decisive variables obtained during HTC optimization

<table>
<thead>
<tr>
<th>No.</th>
<th>Main criteria</th>
<th>Values of limits</th>
<th>Set of the optimized parameters $D$ [m], $\beta$ [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$i_{do} = 3.49$</td>
<td>$d_{75} = 1.80$</td>
<td>$p = 1.30$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$p = 2.0$</td>
<td>$i_{do} = 2.00$</td>
<td>$p = 1.30$</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$d_{75} = 3.77$</td>
<td>$i_{do} = 2.00$</td>
<td>$d_{75} = 1.80$</td>
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</tbody>
</table>

3.3.2. Influence of the limits

Numerical analysis of the influence of the limits on possible values of the main criteria that can be obtained was performed for the criteria converted into the limit values as listed in Table 6. Initially, the values of the main criteria without consideration of the limits were calculated based on data listed in Table 3. The obtained results are shown in Table 7. Next, the limits were introduced and the maximum value of the main criteria was looked for while fulfilling conditions of the criteria converted into the limits. The desire was to obtain the maximum value of the main criteria under the largest possible values of the limits. Sample calculation results are shown in Table 8.

From a comparison of the results shown in Tables 7 and 8 it can be concluded that the limits have significant influence on the value of the main criteria with the exception of HTC range of high efficiencies $d_{75}$. In case of criteria $i_{do}$ and $p$ the influence is more significant. On the other hand the influence on the maximum efficiency $\eta_{max}$ is negligible.
### Table 7. Maximum values of the main criteria calculated without limits

<table>
<thead>
<tr>
<th>No.</th>
<th>Main criteria</th>
<th>Criteria value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(i_{do})</td>
<td>4.27</td>
</tr>
<tr>
<td>2</td>
<td>(\eta_{\text{max}})</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>(d_{75})</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>(p)</td>
<td>4.31</td>
</tr>
</tbody>
</table>

### Table 8. Values of the main criteria obtained with the assumed values of the criteria converted into limits

<table>
<thead>
<tr>
<th>Value of the main criteria</th>
<th>Value of limits</th>
<th>Value of the main criteria</th>
<th>Value of limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i_{do}) = 3.17</td>
<td>(\eta_{\text{max}} = 0.83)</td>
<td>(d_{75} = 2.0)</td>
<td>(i_{do} = 2.00)</td>
</tr>
<tr>
<td></td>
<td>(d_{75} = 1.85)</td>
<td></td>
<td>(\eta_{\text{max}} = 0.80)</td>
</tr>
<tr>
<td></td>
<td>(p = 1.3)</td>
<td></td>
<td>(p = 2.50)</td>
</tr>
<tr>
<td>(\eta_{\text{max}} = 0.90)</td>
<td>(i_{do} = 2.30)</td>
<td>(d_{75} = 1.85)</td>
<td>(i_{do} = 2.00)</td>
</tr>
<tr>
<td></td>
<td>(d_{75} = 1.85)</td>
<td></td>
<td>(\eta_{\text{max}} = 0.85)</td>
</tr>
<tr>
<td></td>
<td>(p = 1.80)</td>
<td></td>
<td>(d_{75} = 1.80)</td>
</tr>
</tbody>
</table>

### 3.3.3. Influence of the optimized parameters

In order to analyze the influence of the optimized parameters on the optimization results, calculations for blade angles were performed. These variables according to literature [2–3] have significant influence on the HTC characteristics. Two blade angle ranges were selected: wide and narrow. The blade angle values for such ranges are shown in Table 9. Optimization was performed for the pre-selected main criteria \(i_{do}, \eta_{\text{max}}, d_{75}, p\) for the angle ranges provided from the actual construction according to Table 9. The obtained optimal result values of main criteria are shown in Table 10.

### Table 9. Angle ranges \(\beta[^\circ]\) selected to optimization calculations

<table>
<thead>
<tr>
<th></th>
<th>(\beta_{11w})</th>
<th>(\beta_{12w})</th>
<th>(\beta_{21w})</th>
<th>(\beta_{22w})</th>
<th>(\beta_{31w})</th>
<th>(\beta_{32w})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide angle range</td>
<td>60–130</td>
<td>60–150</td>
<td>30–100</td>
<td>120–160</td>
<td>60–150</td>
<td>10–60</td>
</tr>
<tr>
<td>Narrow angle range</td>
<td>95–120</td>
<td>110–120</td>
<td>50–70</td>
<td>135–140</td>
<td>80–100</td>
<td>30–40</td>
</tr>
</tbody>
</table>

### Table 10. Values of the main criteria for angle ranges taken from actual HTC constructions for wide and narrow angle range

<table>
<thead>
<tr>
<th>Angle Range</th>
<th>Optimization criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(i_{do})</td>
</tr>
<tr>
<td>Actual contractions per Table 3</td>
<td>4.27</td>
</tr>
<tr>
<td>Narrow angle range per Table 9</td>
<td>2.75</td>
</tr>
<tr>
<td>Wide angle range per Table 9</td>
<td>4.33</td>
</tr>
</tbody>
</table>

After comparing the results shown in Table 10 it can be concluded that the range variation of blade angles has a significant influence on the values of the main criteria.
with the exception of the HTC range of high efficiencies – $d_{75}$. The influence of the angle value range on the optimal value of the main permeability criteria $p$ is very significant. In case of criteria $l_{do}$, the influence is less significant, but it is negligible for maximum efficiency $\eta_{\text{max}}$ and $d_{75}$.

Based on these results it can be concluded that there is a certain blade angle value range where good efficiencies can be obtained.

3.3.4. Calculations time

Time required for one optimization calculation cycle for a number of 5000 generations and a population size equal to 100 with 16 parameters on Pentium IV, 3.1 GHz computer was about 12 hours.

In order to shorten calculation time a parallel genetic algorithm was also applied. The parallel genetic algorithm calculates evolution of two populations at the same time. After a certain number of generations an exchange of some parameters values occurs and further evolution calculation takes place. Such procedure lasts until optimal value is obtained. Application of the parallel genetic algorithm neither provided better results nor shortened the time of calculations. Based on this analysis it can be concluded that the application of evolution methods other than a genetic algorithm to the optimization of HTC construction is not necessary, because the genetic algorithm allows to provide satisfactory results in reasonable time much shorter than other random numerical methods.

4. Evaluation of optimization calculations

During the optimization of the HTC construction sets of sub-optimal parameters required to fabrication initiation were obtained. From the calculated sets of parameters shown in Table 6 one set needs to be chosen. The parameter values should be convenient from technological aspects, providing higher value of the main criteria and satisfactory values of criteria converted to limits at the same time. For example, an HTC impeller blade with small inlet angle is easier to fabricate than a blade with large inlet angle. Furthermore it is desired to obtain the proper shape of the flow channel with limited curvature, small length and small hydraulic radius (small ratio of channel cross section area and its circumference). Based on the selected set of optimized parameters the shape of the HTC working area is determined through blade core and shell profiles. This data allows building a 3-D model of HTC impellers using the available CAD software [5].

From the analysis of the construction process of the HTC working area it can be concluded that the determination of the optimized parameters is not sufficient but necessary in order to obtain the optimal HTC working area construction. An optimal working area is considered as area that provides minimal flow through losses and the least technological problems during fabrication. The working area geometrical shape also
depends on: curvature angle of the inlet blade edge, an angle along the blade edge and a bending angle along the inlet blade length [8, 15].

Based on the analysis of the influence of blade angle range changes it can be concluded that HTC construction with high values of $d_{75}$ and $\eta_{\text{max}}$ criteria can be obtained under limited range of blade angles. It concurs with conclusions provided in [8, 15] dissertations that selection of angle values beyond the typically applied range in the existing HTC constructions almost always leads to worse construction quality. The optimization calculations also confirm opposite influence of maximum efficiency $\eta_{\text{max}}$ and dynamic ratio $i_{do}$ on HTC characteristics (for HTC construction with high values of $i_{do}$ the maximum efficiency $\eta_{\text{max}}$ HTC is smaller).

The application of genetic algorithm allows to obtain accurate results within several hours, the genetic algorithm is efficient, calculative and determinative [3]. Furthermore genetic algorithm is universal and it can be applied to estimation and optimization calculations of HTC with more accuracy and certainty of obtaining global optimum than other previously applied optimization methods.

5. Conclusions

In this paper construction optimization of HTC with application of genetic algorithm was described. The scope of this optimization contains optimization of HTC impeller working area. Multi-objective type of optimization was applied. As main optimization criteria was selected: a value of torque ratio for $i_k = 0$, therefore $i_{do}$, HTC efficiency – $\eta_{\text{max}}$, HTC permeability – $p$ and HTC range of high efficiencies – $d_{75}$. These criteria should obtain maximum value. As optimized parameters the following were selected: HTC active diameter, HTC meridional cross section and blade angles on core and shell, overall 16 parameters. The ranges of value for these parameters were selected based on values obtained from fabricated HTC constructions. A model of multiple streams was used as the mathematical model. Sample calculation for HTC type HTC 410. Selected parameters of the model were estimated based on analysis of HTC type HTC 410. As a result of these calculations sub-optimal set of parameters were obtained. These parameters are the output data for further construction.

References


Optymalizacja konstrukcji przekładni hydrokinetycznej z użyciem algorytmu genetycznego