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THERMODYNAMIC OPTIMISATION OF DIESEL ENGINE TURBOCHARGING SYSTEM

PART II

The authors present the optimisation procedure and results, applied to the system discussed in part I. This procedure utilises a "fixed variables" method from the group of "search methods". The optimisation is related to the specific turbocharged engine STAR T370 for which necessary construction data and experimental measurements were available. Calculation results, however, are based mainly on the computer simulation of time dependant flows in the inlet and exhaust systems of this engine. They show that the presented method, after necessary improvements and the use of more advanced optimisation procedures, could represent an additional and attractive tool, which might be used by designers of such systems.

NOMENCLATURE

$\dot{B}$	–	exergy flux,
$\Delta\dot{B}$	–	external loss of the exergy flux,
$\delta\dot{B}$	–	internal loss of the exergy flux,
$\Sigma\,\delta\dot{B}_i$	–	sum of irreversible internal losses of the exergy flux,
c_p	–	specific heat at constant pressure,
c_v	–	specific heat at constant volume,
D	–	pipe diameter,
F	–	duct cross-sectional area,
L_t	–	technical work,
l	–	pipe length,

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m	–	mass,
$\dot{m}$	–	mass flowrate,
M	–	torque,
N	–	rate of work transfer (power),
n	–	rotational speed,
p	–	pressure,
R	–	gas constant,
T	–	absolute temperature,
u	–	velocity,
x	–	co-ordinate,
Y	–	criterion function,
$\Delta\alpha$	–	valve overlap angle,
η	–	efficiency,
λ_f	–	friction number,
π	–	pressure ratio function,
ρ	–	density,
ω	–	weight factor.

Subscripts

0	–	reference conditions, or original design,
a	–	air,
c	–	cylinder, or cycle,
C	–	compressor,
cool.	–	cooling medium,
IC	–	intercooler,
ext	–	external,
i	–	isentropic,
M	–	maximum torque conditions,
N	–	nominal power conditions,
T	–	turbine,
s	–	exhaust gas,
V	–	valve.

1. The choice of optimisation method

The optimisation problem of a turbocharging system, defined in part I of this work, is complex. Acquiring the data for the analysis of this system from the numerical simulation is laborious and time consuming. Time dependant flows in the inlet and exhaust manifolds, described by sets of non-linear differential equations, require this simulation to be performed for a few full engine run-cycles. The number of cycles should be greater than three and it is worth mentioning that the same value is quoted also by other authors [1], [2], [3]. It results from the necessity of achieving in the simulation a full repetition of every numerical parameter value in each simulated cycle – a feature characteristic for a steady-state engine operation. Similar conditions also exist in other non-stationary flow simulation cases (for example [4], [5]).

Taking into account the type and the character of the described optimisation problem, the authors decided to use in the analysis a solution method that would be easy to apply and simple.

After the revision of possible optimisation methods (discussed for example in works [6], [7], [8], [9]), a fixed-variables method from the search (trial and error) methods group has been chosen. Although it is less effective than many of other no-gradient or gradient methods, its algorithm is simple. It is also worth underlining that, at this stage, the main aim of the analysis is to formulate and describe many interconnected thermal and flow phenomena in such a way that the optimisation of the considered system becomes possible.

According to the chosen optimisation method, the criterion function values are calculated in turns for n variables. In each turn, only one chosen variable varies and the remaining (n-1) have fixed values. When the minimum of the criterion function is found for a particular variable, its value is then kept unchanged in calculation for the remaining variables. The described algorithm is logically simple and the results of its application are presented in section 2.

2. The analysis of initial optimisation results

One assumed in the optimisation analysis that the considered Diesel engine works with two different rotational speeds n_M and n_N, related to maximum torque M_{max} and maximum power N_{max}, respectively. All data and quantities experimentally measured for the specific engine operating conditions were used. It was assumed that weight factors for these two speeds are equal, i.e. $\omega_1=\omega_2=\omega=0.5$, therefore, the criterion-goal function had the form:

$$Y = 0.5 \cdot (Y_1 + Y_2) \tag{1}$$

where Y_1 and Y_2 are the values of the function

$$Y_k = \frac{1}{t_{c,k}} \int_0^{t_{c,k}} (\sum \delta \dot{B}_i)dt; \qquad k = 1,2\,,$$

for the two different operating points, related to n_M and n_N. The function Y_k, as it was mentioned in part I, represents the sum of all internal irreversible exergy losses $\delta \dot{B}_i$ in the whole flow path. They are shown in Table 1 and described in detail in [10] and other references.

The optimisation based on this approach was performed for the turbocharged engine STAR T370 inlet and exhaust systems. The basic data of this engine are given in part I of the present work (Table 1). The preliminary calculations carried out in order to establish the character of the criterion function changes, in the region of parameter values representing the existing system, are presented in Figs 1 to 3. The data shown in these figures were obtained assuming that the criterion function had the form $Y=Y_1$ and $Y=Y_2$, for the engine operating conditions related to M_{max} and to N_{max} respectively. These results present a qualitative step forward compared to the initial study reported in [11], where the turbocharging system was analysed in terms of entropy generation rates for slightly different engine operating conditions. Nonetheless, the present paper accounts for the conclusions drawn from the previous study, which is exemplified in the choice of the system parameters (the turbine effective area, the temperature decrease in intercooler and the valve overlap period).

Table 1.

Main irreversible internal exergy losses

System node	Description
Compressor (impeller and diffuser global loss)	$\delta\dot{B}_C = \dot{m}_C T_0 c_{p.a} \ln\left[\frac{1}{\pi_C} + \frac{1-\frac{1}{\pi_C}}{\eta_{iC}}\right]$
Turbine (inlet channel and rotor global loss)	$\delta\dot{B}_T = \dot{m}_T T_0 c_{p.s} \ln\frac{1+(\pi_T - 1)\cdot\eta_{iT}}{\pi_T}$
Intercooler	$\partial\dot{B}_{IC} = \dot{m}_C T_0\left[c_{p.a}\ln\frac{T_{a2}}{T_{a1}} - R\ln\frac{p_{a2}}{p_{a1}} - \frac{c_{p.a}(T_{a2}-T_{a1})}{T_{cool}}\right]$
Flow local losses (valves and manifold)	$\delta\dot{B}_{1-2} = -\dot{m}_1 R T_0 \ln\left(1 - \frac{\Delta p_{1-2}}{p_1}\right)$
Flow frictional losses	$\delta\dot{B}_f = 1/4\pi D\lambda_f T_0 \int_l (\rho u \frac{u^2}{2}\frac{1}{T})dx$

Changes of the normalised irreversible exergy losses $\delta\dot{B}/\delta\dot{B}_0$ were calculated as functions of the chosen decision variable or parameter – with values of the remaining ones kept fixed. Figs 1 to 3 also show changes of the exergy losses related to constraint conditions (i.e. m_c, L_t and $\Delta\dot{B}_{ext}$) in the analysed optimisation. The losses were normalised with respect to the values associated with the ones in the original construction of the analysed engine inlet and exhaust systems (they are denoted by subscript "0").

In many cases, it can be seen that the plots of the criterion function $\delta\dot{B}/\delta\dot{B}$ versus different variables have rather flat shapes. There are, however, decision variables which have significant influence on the change of this criterion function.

The highest diversification of this function, about 25%, is observed in Fig. 1a when the ratio F_T/F_p changes between 0.22 and 0.33 – for two different engine operating conditions related to M_{max} and to N_{max}. Quantities F_T and F_p are the turbine equivalent cross-sectional area and the cross-sectional area of the pipe delivering exhaust gas to the turbine, respectively. It is clear that the criterion

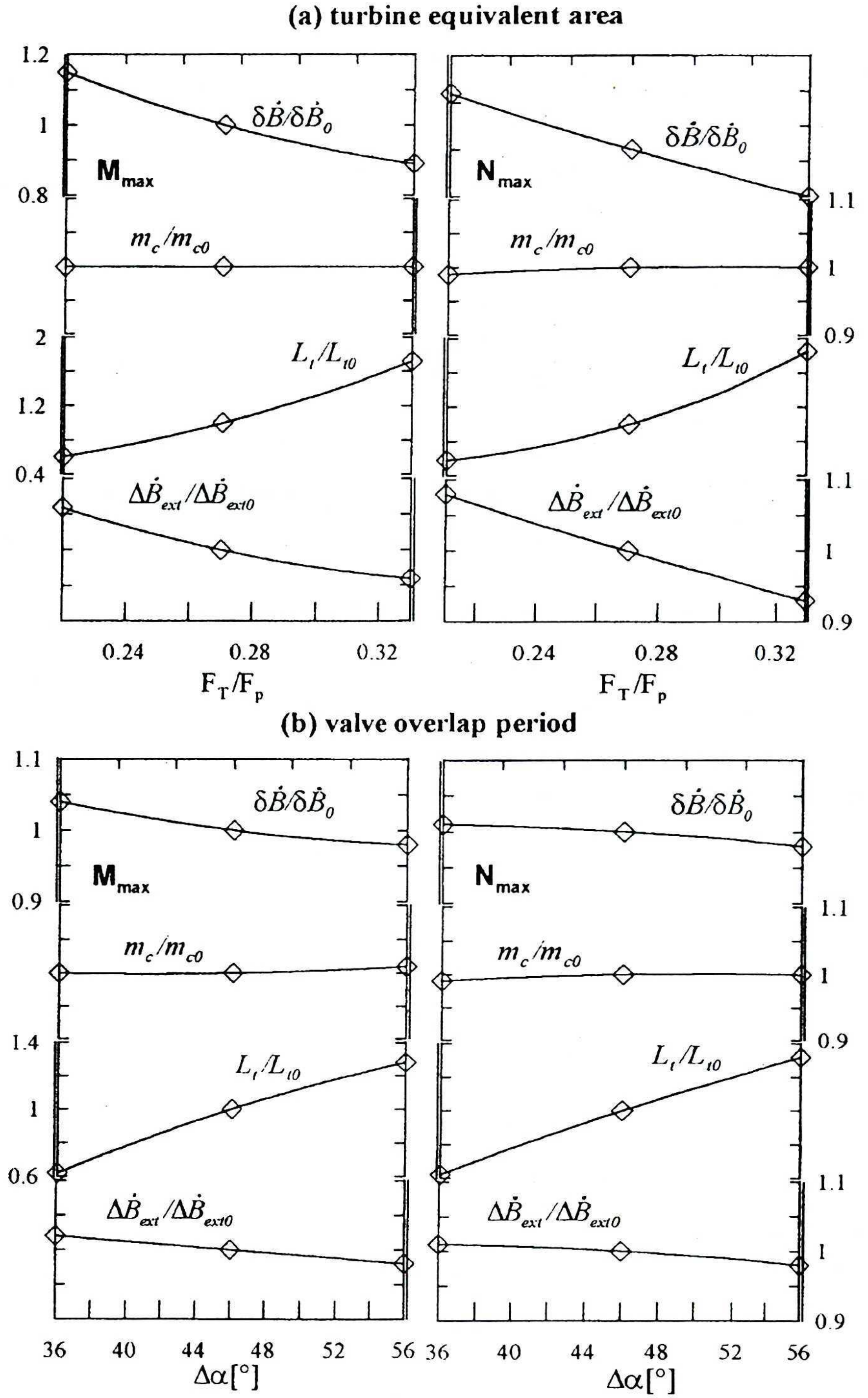

Fig. 1. Irreversible exergy losses vs turbine effective area (a) and vs valve overlap period (b)

function decreases for the growing ratio of F_T/F_p, and reaches a minimum value on its right hand side edge for the considered ratio range. However, it is important to notice that the point related to the minimum of $\delta\dot{B}/\delta\dot{B}$ lies in the permissible range of decision variable values. This is confirmed by plots of normalised values of three constraint conditions in the same Fig. 1a. The total air mass, charged into all cylinders, m_c, remains nearly unchanged. The positive value of the cylinder charge-exchange work, L_t, is greater than its respective original construction value. At the same time, the exhaust waste-heat, $\Delta\dot{B}_{ext}$, decreases in the whole considered F_T/F_p – range. It should be noted that the m_c result reported in [11] shows a drop down by about 2% relative to the original design value. This probably results from different conditions of gas flow induced by slightly different initial in-cylinder conditions in the two cases.

Significant diversification of criterion function is also visible in Fig. 1b, where influence of the inlet and exhaust valve overlap period, $\Delta\alpha$, is shown for both engine operating conditions. The changes are smaller than before: 6% and 3% for conditions related to M_{max} and to N_{max} respectively, for this overlap period growing in both cases from 36° do 56°. The criterion function reaches its minimum on the right hand side edge of the analysed range, for both operating conditions, as in Fig. 1a. Similarly, the three constraint conditions related to m_c, L_t, and $\Delta\dot{B}_{ext}$ values are satisfied – since $m_c/m_{c0} > 1$, $L_t/L_{t0} > 1$, and $\Delta\dot{B}_{ext}/\Delta\dot{B}_{ext0} < 1$.

The third decisive variable in the analysis, which has a noticeable influence on the criterion function, is the decrease of intercooler temperature, ΔT. The respective plots are shown in Fig. 2a for both engine operating conditions.

The diversifications of $\delta\dot{B}/\delta\dot{B}_0$ are about 11% and 1% for the maximum torque and the nominal power conditions, respectively. The intercooler ΔT – decrease for both conditions is within the range 0 to 27 K. In both cases, one can observe a clear increase of the total air mass m_c charged into all cylinders - for a growing value of ΔT. This feature is consistent with the influence of ΔT observed in practice. It can be regarded as a confirmation of the proposed analytical approach, and also as a positive verification of the program developed for numerical simulation of all processes involved in Diesel engine turbocharging system.

The influence of the decrease of the intercooler air temperature on the criterion function $\delta\dot{B}/\delta\dot{B}_0$ is, however, different from the respective influences related to the other two decision variables discussed earlier. Although the increase of ΔT-value facilitates the fulfilment of constraint conditions (Eqs 10 to 12 in part I) it also causes the increase of the criterion function. This means that the positive effect of the air temperature decrease (an increase of the total air mass m_c) occurs at an expense of the overall turbocharging system efficiency. This is confirmed by plots in Fig. 2a, related to L_t/L_{t0} and $\Delta\dot{B}_{ext}/\Delta\dot{B}_{ext0}$ – as

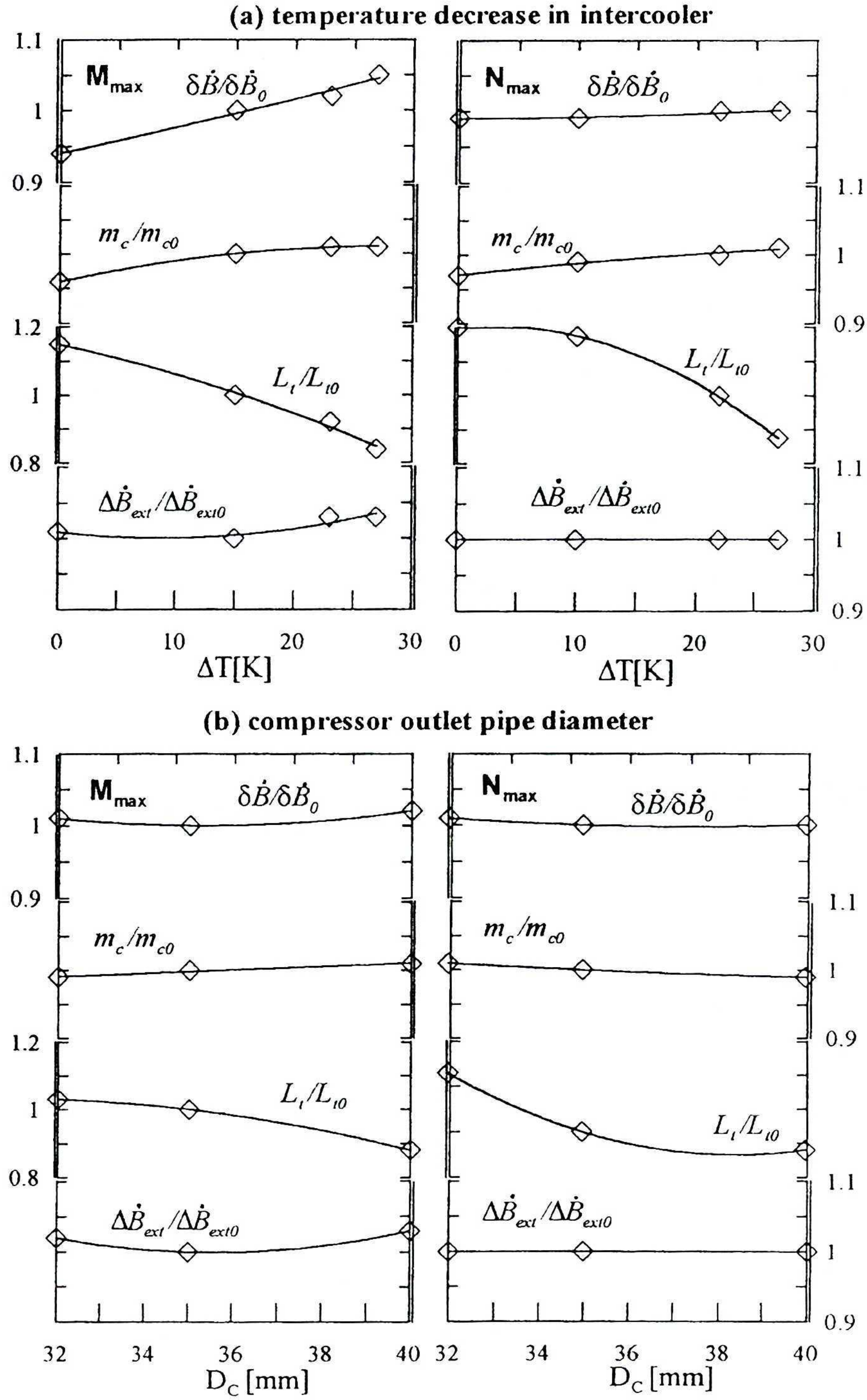

Fig. 2. Irreversible exergy losses vs air temperature decrease in intercooler (a) and vs compressor outlet pipe diameter (b)

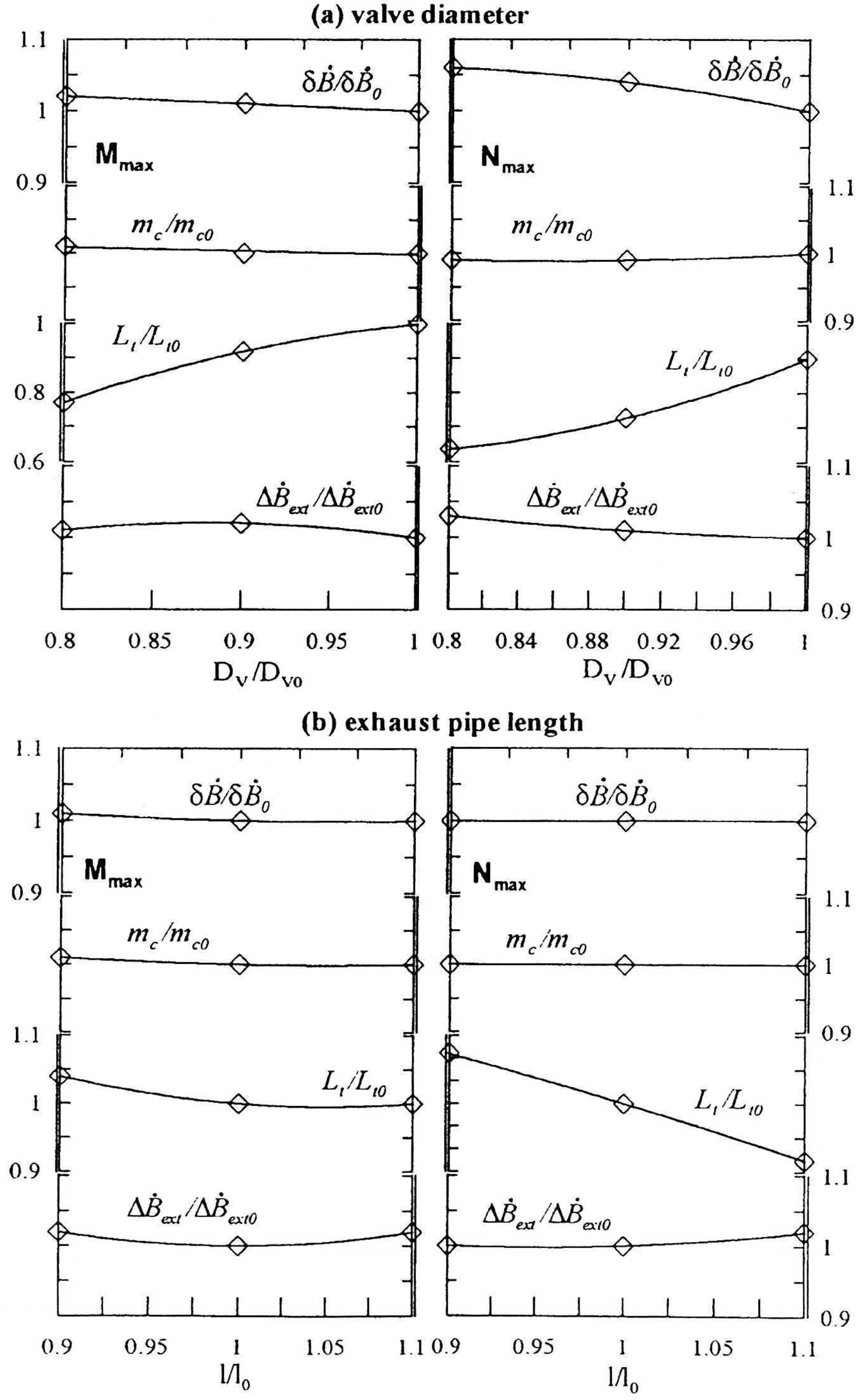

Fig. 3. Irreversible exergy losses vs exhaust valve diameter (a) and vs exhaust pipe length (b)

functions of ΔT – value. It is clear that the in-cylinder work done during the charge exchange period, L_t, decreases substantially and the exhaust waste-heat loss, $\Delta\dot{B}_{ext}$, increases. Therefore, one can expect that the optimal intercooler ΔT – decrease should have a value not greater than in the original construction.

The influence of the compressor outlet pipe cross-sectional area D_C on the normalised irreversible exergy losses $\delta\dot{B}/\delta\dot{B}_0$ is shown in Fig. 2b. It is rather small, and the minimum of criterion function in the analysed range appears at the original construction value. Although for greater diffuser diameters there is an increase of the total air mass m_c charged into all cylinders, it is, however, associated with a decrease of the in-cylinder work L_t done during the charge exchange period and with an increase of the exhaust waste-heat loss $\Delta\dot{B}_{ext}$.

A general and obvious decreasing tendency of the criterion function can be observed – when the flow cross-sectional area of valve gaps increases (diameters of inlet and exhaust valves always change simultaneously and by the same degree – see Fig. 3a). Falls of the irreversible exergy losses $\delta\dot{B}/\delta\dot{B}_0$, by 3% and 6% for operating conditions related to M_{max} and N_{max}, respectively. These are not connected with any noticeable change of the total air mass, m_c, and of the exhaust waste-heat loss, $\Delta\dot{B}_{ext}$. The in-cylinder work L_t, however, increases by about 20% and 50% for these operating conditions, respectively.

Fig. 3b presents the influence of the length of the pipe delivering exhaust gas to the turbine on the irreversible losses $\delta\dot{B}/\delta\dot{B}_0$. For the analysed length range, the criterion function changes only by about 1%. The total air mass m_c changes likewise. Taking into account the other two constraint conditions, one can see that this original length is really very close to the optimal value.

3. Results of optimisation for specific engine

The analysis in Section 2, presented in Figs 1 to 3, shows only a sample of the initial optimisation results. However, they give a ground to apply the method of minimum exergy irreversible loss to optimise the inlet and exhaust system of a specific turbocharger Diesel engine. From the list of decision variables, listed in part I, the following ones were chosen for the use in the system optimisation:

– valve overlap period,
– turbine equivalent area,
– air temperature decrease in the intercooler.

These variables have the most significant influence on the criterion goal function. The results of the optimisation based on the so called 'fixed-variables method' are listed in Table 2 – together with the original system values. Improvements of this system are characterised by an increased value of the valve overlap period (up to $\Delta\alpha$=56°) and a slightly greater value of the turbine equivalent area F_T/F_p=0.29. The influence of the third variable, the turbocharged air ΔT–decrease, is smaller than the two just mentioned – although in this case a flat minimum can be detected as well.

Table 2.

Comparison between the original system design and the design improved by minimisation of the irreversible exergy losses

original design of the system		after optimisation	
$F_T/F_p = 0.27$		$F_T/F_p = 0.29$	
$\Delta\alpha = 46°$		$\Delta\alpha = 56°$	
ΔT=15 K (M_{max}) / 22 K (N_{max})		a little impact of cooling was noted for the range of temperature drop	
		ΔT=13-23 K (M_{max}) / 17-24 K (N_{max})	
constraint conditions:		constraint conditions:	
M_{max}	N_{max}	M_{max}	N_{max}
$\dot{m}_c$=0.0787 kg/s	0.1480 kg/s	$\dot{m}_c$=0.0794 kg/s	0.1480 kg/s
L_t = 76.2 W	-59.9 W	L_t =125.8 W	-35.0 W
$\Delta \dot{B}_{ext}$=14944 W	34667 W	$\Delta \dot{B}_{ext}$=14243 W	33176 W
$\Sigma\delta \dot{B}_i$= 5258 W	15922 W	$\Sigma\delta \dot{B}_i$= 4877 W	15159 W

Additional illustrations of this optimisation, for engine operating conditions related to M_{max} and N_{max}, are presented in Fig. 4 – all for the value of the turbine equivalent area F_T/F_p=0.29. The following normalised value plots are shown there: the criterion function and all constraint conditions as functions of the valve overlap period (in Fig. 4a) and of the intercooler air temperature decrease (in Fig. 4b). All plots of the criterion function $\delta\dot{B}/\delta\dot{B}_0$ have a clear minimum in the analysed range of variables $\Delta\alpha$ and ΔT – apart from the one for ΔT and working condition related to N_{max} (shown in Fig. 4b). Calculations also show that the sum of irreversible exergy losses for the improved system is lower compared to the original one, by about 1% of engine power.

4. Conclusions

The presented attempt of the optimisation of a Diesel engine turbocharging system is based on the thermodynamic approach. The main criterion of this optimisation is the goal function, defined as the sum of irreversible exergy losses occurring in the whole system considered. It is shown that this function depends upon the characteristic design parameters and control settings of the system, as well as its operating conditions.

The authors analysed and presented the influence on the goal function value of the following quantities variations: turbine equivalent area, time diagrams of the inlet and exhaust valves, valves overlap period, air temperature decrease in the intercooler, exhaust manifold length and compressor diffuser. The goal

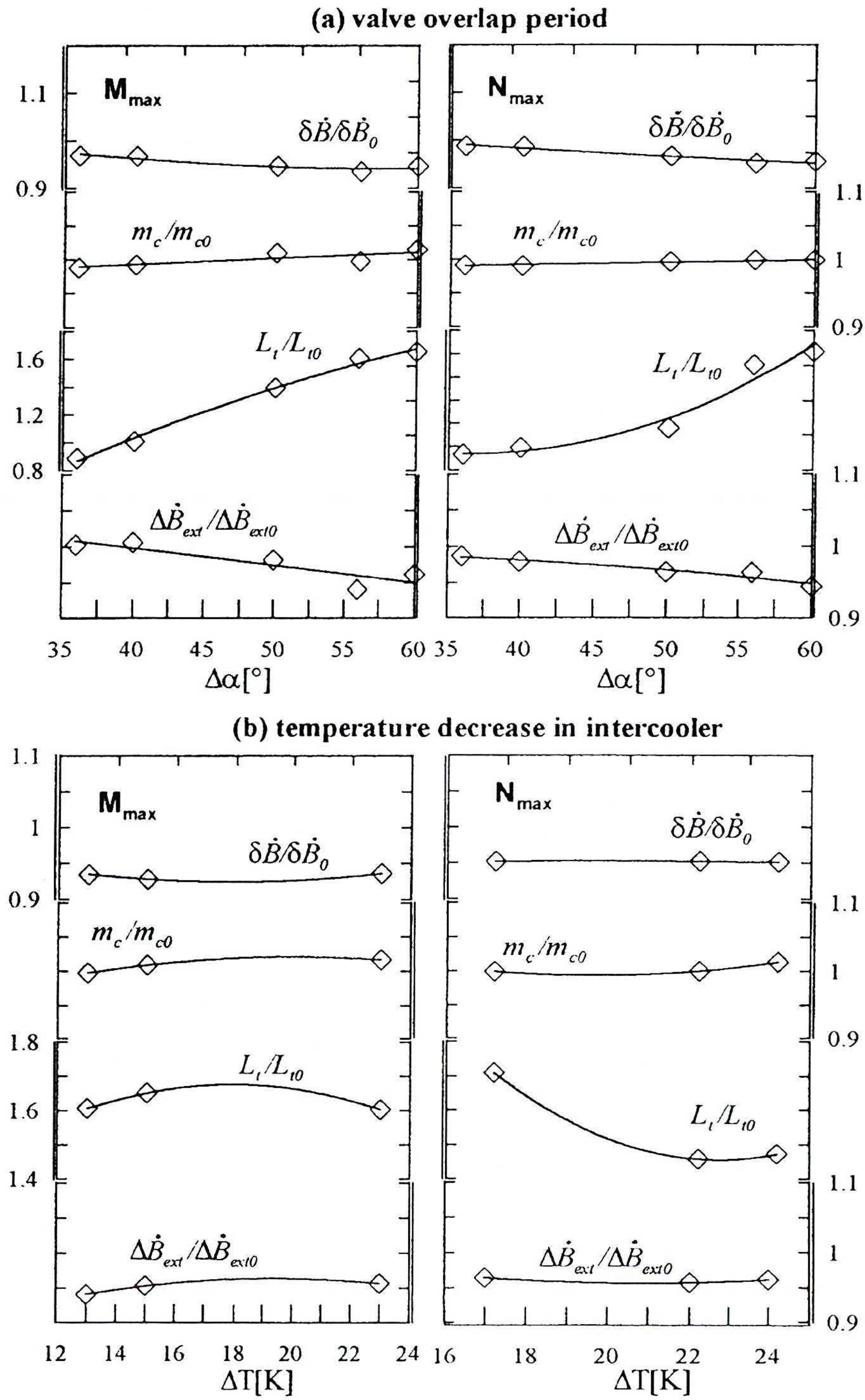

Fig. 4. Computational resuls for the improved system design (F_T/F_p=0.29)

function depends also on other system parameters, but these just listed – treated as decision variables – characterise the influence of basic subsystems on the irreversible losses.

For many different parameters and their respective ranges analysed, the criterion function shows a rather small change. However, the influences of decisive variables, in particular the turbine equivalent area, valve overlap period and intercooler air temperature decrease are substantial.

An improved set of design parameters has been proposed for the turbocharged engine STAR T370 as a result of the application of the presented optimisation method. It allows a more efficient work of this engine under two basic operating conditions characterising engine performance, related to the rotational speeds n_M-n_N. This improved set, presented together with the original values in Table 2, suggests the following:

- the increase of the inlet and exhaust valve overlap period from 46° to 56°,
- the increase, by about 7%, of the turbine equivalent area F_T/F_p, from 0.27 to 0.29.

The results of the presented analysis confirm that:

- the exergy analysis represents a practical and useful method for the improvements of the charge exchange system design and for the choice of parameter values which are relevant and characteristic for this system work,
- the choice of the criterion function in the form of the sum of irreversible exergy losses facilitates the thermodynamic optimisation of the turbocharged engine inlet and exhaust system.

Finally, it is important to state that the optimisation procedure needs to be improved in two respects.

Firstly, more advanced optimisation methods should be implemented in the analysis. This will certainly make it possible to find a solution of the discussed problem in a more effective and reliable way.

Secondly, future theoretical work should also include internal cylinder processes in the analysis. Owing to this approach, the use of experimental data or constraint conditions will not be necessary, and a complete analysis of a whole turbocharged engine will become possible.

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Termodynamiczna optymalizacja układu turbodoładowania silnika wysokoprężnego

Część II

Streszczenie

W tej części pracy przedstawiono prostą procedurę optymalizacyjną dla układu określonego w części I. Wykorzystano w niej metodę ustalania zmiennych z grupy metod poszukiwań. Optymalizacja dotyczy 4-cylindrowego silnika wysokoprężnego STAR T370, dla którego dysponowano niezbędnymi danymi konstrukcyjnymi i pomiarowymi. Rezultaty obliczeń bazowały głównie na symulacji komputerowej zmiennych w czasie przepływów w układzie dolotowo-wylotowym tego silnika. Przedstawione wyniki świadczą, że po zastosowaniu efektywniejszych procedur optymalizacji prezentowana metoda może stanowić dodatkowe i użyteczne narzędzie dla konstruktorów układów turbodoładowania.