Ways to improve the efficiency of an automotive thermoelectric generator

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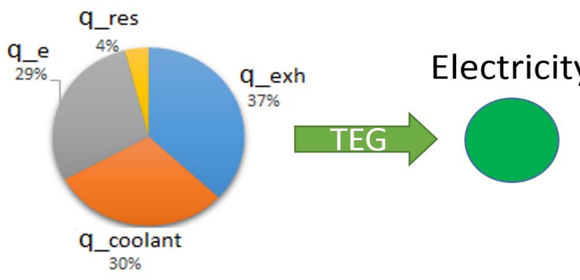
Motivation

Combustion engines are the main source of energy for many vehicles, which generate about 90 % of total power of the transport power systems.

Efficiency of modern ICE is about 30-40%. But it can be increased by a number of ways:

1. Turbo-compound engine
2. Stirling cycle
3. Rankine cycle
4. Turbocharging
5. **TEG**



Main problems of TEG implementation
1. High price
2. Relatively low efficiency

The efficiency of the thermoelement

$$\eta = \frac{T_h - T_c}{T_h} \cdot \frac{M-1}{M + (T_c/T_h)} = \eta_k \cdot \eta_{TT}$$

$$R_{load} / r_{TEG} = M = \sqrt{1 + 1/2Z(T_h + T_c)}$$

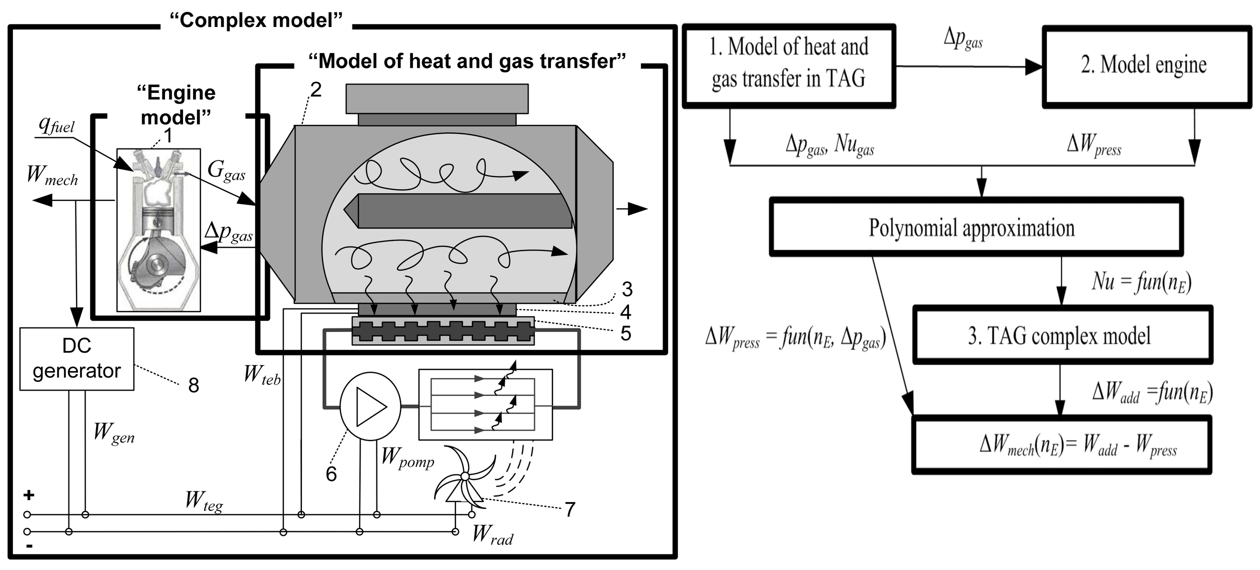
Main ways to improve the efficiency of automotive thermoelectric generators:

- Use of more efficient thermoelectric materials
- Design optimization:
  - Increase temperature difference between thermoelement junctions
  - Increasing of the heat transfer from the heat source (exhaust gases, gases of industrial enterprises, etc.) to thermoelement junctions
  - Thermal resistance reduction in the TEG construction

The main Goal of our research → Reduction of electrical losses (Poster # P72)

Methods/modeling

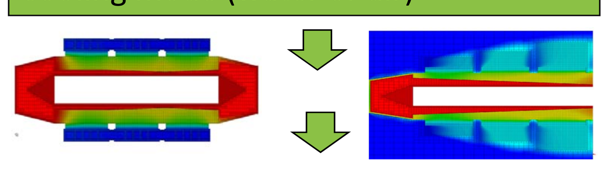
Physical effects, affecting the TEG Qualitative characteristics



CFD simulation | Heat transfer modeling | **Analytical modeling**

Goal: Exact describing heat transfer & gas dynamics

Model input:
n_E engine rotation speed
T_{eg} Exhaust gas temperature
Cooling mode (water or air)



Model results for some typical modes:
- Exhaust pressure lost Δp_{eg}
- temperature distribution
- convection heat transfer coefficients α_h, α_c

Goal: construction parametric optimization

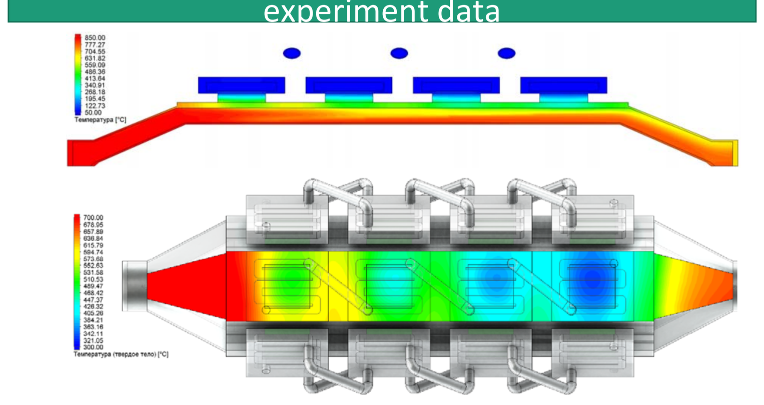
Model input: Any numerical parameters variance

1. Thermal conductivity
2. Zeebek effect
3. Heat transfer and air resistance into the TEG
4. Effect of aerodynamic resistance TEG on ICE

Model results:
- heat flux Q_{hot}
- thermo-electric power W_{teb}
- change of engine power ΔQ_{mech}

CFD model

CFD model was created and verified on experiment data



Methods:
* Steady-state flow of homogenous exhaust gases is modeled with a finite volume method.
* Steady-state heat transfer in solid bodies modeled with finite element method.

FlowSimulation & **AVL Fire** software.

Model results for some typical modes:
- Exhaust pressure lost Δp_{eg}
- temperature distribution W_{teb}
- average convection heat transfer coefficients α_h, α_c

CFD model simulates exhaust gases and cooling liquid flows. It allows to calculate temperatures, pressures and heat flows.

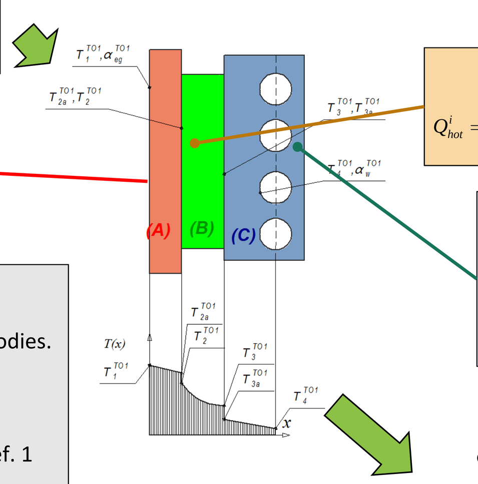
Analytical Heat transfer modeling

Model input:
T_2, T_3 *hot & cold soldered joint temperature*
***Q** heat flux*

Hot exchanger

$$Q^i_{hot} = k_{i\_eg}\alpha_h S_1 \left(T^i_{eg} - T^i_1\right)$$

$$Q^i_{hot} = \frac{T^i_1 - T^i_2}{\frac{2\delta_A}{(S_1+S_2)\lambda_A} + \frac{\delta_{case}}{S_2\lambda_{case}}}$$



TEB

$$Q_{hot} = Q^i_{cold} + W^i_{teb} = \frac{(S_2+S_3)\bar{\lambda}_B\left(T^i_2 - T^i_3\right)}{2\delta_B} + \frac{W^i_{teb}}{2}$$

Cold exchanger

$$Q^i_{cold} = k_{i\_w}\alpha_c S_4\left(T^i_4 - 0.5\left(T^i_{w1} + T^i_{w2}\right)\right)$$

$$Q^i_{cold} = \frac{T^i_3 - T^i_4}{\frac{2\delta_C}{(S_3+S_4)\lambda_C} + \frac{\delta_{case}}{S_3\lambda_{case}}}$$

$$\alpha_h, \alpha_c = function(\mathrm{Nu}, \mathrm{Re}, \mathrm{Pe})$$

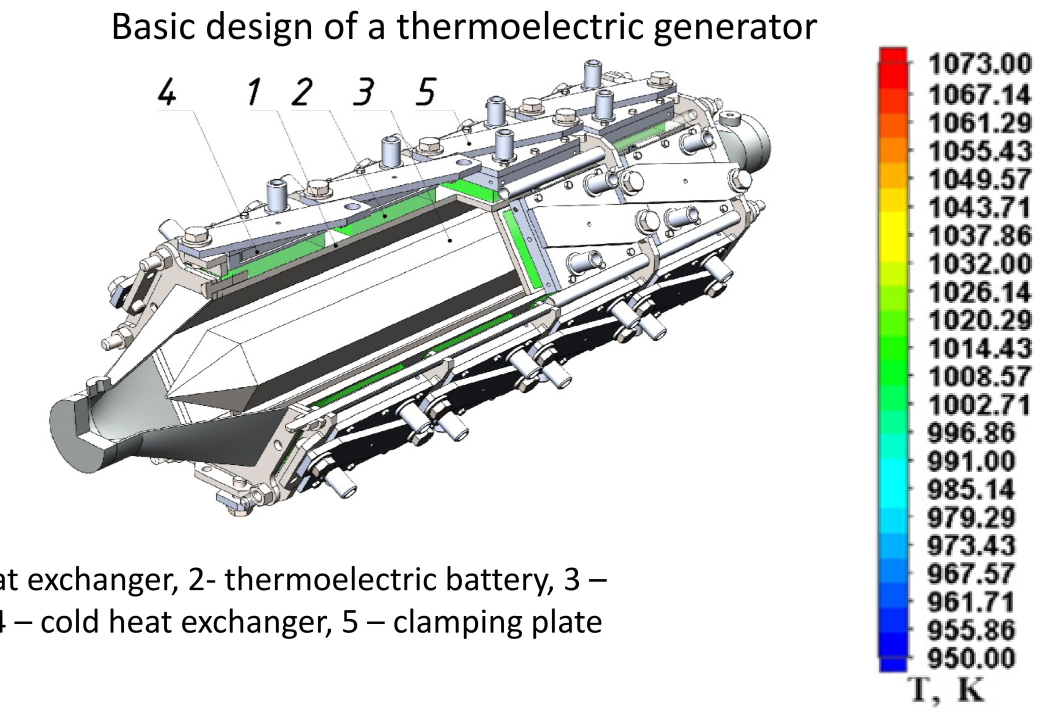
Main hypothesis:
* 1D heat flow through laminate plate.
* Fourier low for heat transfer in solid bodies.
* Convective condition (α=const or α=variable).
* Thermoelectric characteristics were measured using methods described in ref. 1
* Steady-state problem.

Methods: genetic algorithm, Neldor- Mead method for solving nonlinear system equations
MATLAB program

Model results:
- TEB parameters S_p, S_n
- thermo-electric power W_{teb}

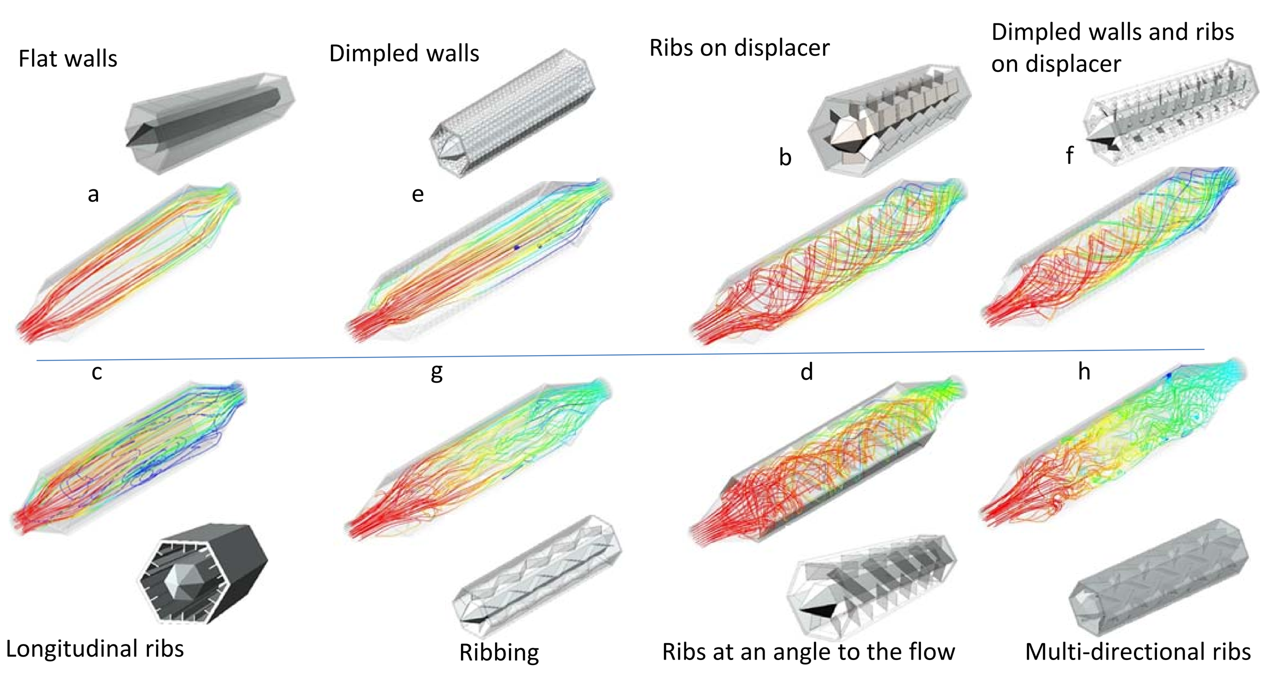
Results

Basic design of a thermoelectric generator

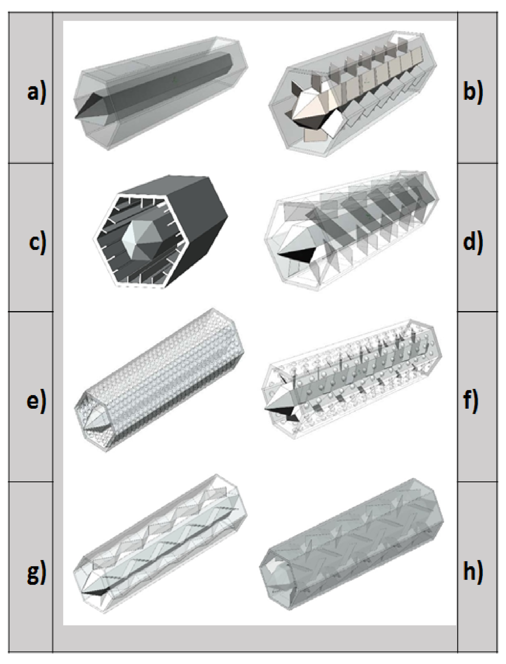


1 – hot heat exchanger, 2- thermoelectric battery, 3 – displacer, 4 – cold heat exchanger, 5 – clamping plate

Waste gases flow modelling



CFD modeling results



Influence of heat exchanger type at:
- aerodynamic resistance Δp_{teg}
- mean heat transfer coefficient
- Nu

№	Q_{hot}, W	Δp_{teg}, Pa	$\frac{Nu}{Nu_a}$	$\frac{\xi}{\xi_0}$	$\frac{Nu\xi_0}{Nu_a\xi}$
a	5317	955	1	1	1
b	7804	4705	1.52	4.93	0.309
c	7546	1921	1.61	2.01	0.801
d	7593	4846	1.47	5.07	0.291
e	7184	2357	1.35	2.47	0.547
f	8748	4875	2.08	5.10	0.408
g	7661	2787	1.47	2.92	0.505
h	8644	6419	1.42	6.72	0.211

Nu - Nusselt number
Nu_0 – Nusselt number for heat transfer design without intensifier
ξ – loss factor
ξ_0 – loss factor for construction without heat intensifiers
λ - coefficient of thermal conductivity, W / m · K
l – characteristic size, м (the length of the hot heat exchanger)
α – heat transfer coefficient
ΔP – pressure drop, Па
ρ – density of gases, кг/м^3
V – average exhaust gas flow rate, м/с

$$\xi = \frac{2 \cdot \Delta P}{\rho V^2}, Nu = \frac{\alpha \cdot l}{\lambda},$$

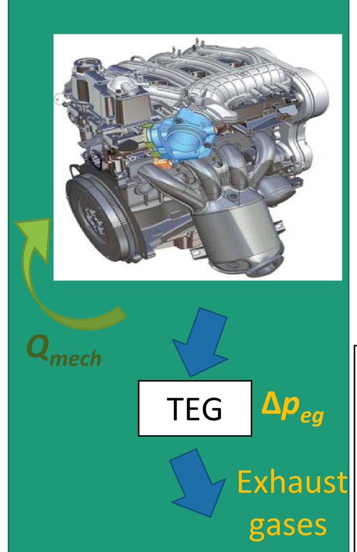
Modelling of effect of aerodynamic resistance TEG on power ICE

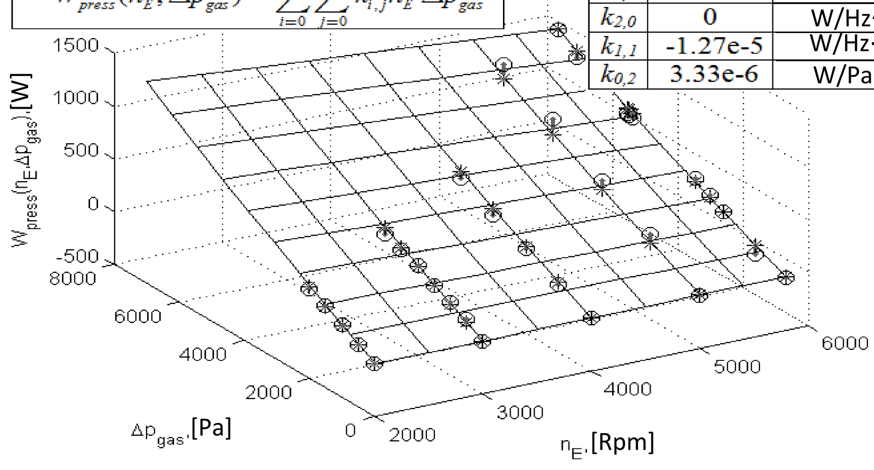
Gasoline engine VAZ 21127
106 HP (78 kW)
800...5800 rpm
Max. torque, 148 Nm

Calculation of power losses
Approximation of power losses

$$W_{press}(n_E, \Delta p_{gas}) = \sum_{i=0}^{2}\sum_{j=0}^{2} k_{i,j} n_E{}^i \Delta p_{gas}{}^j$$

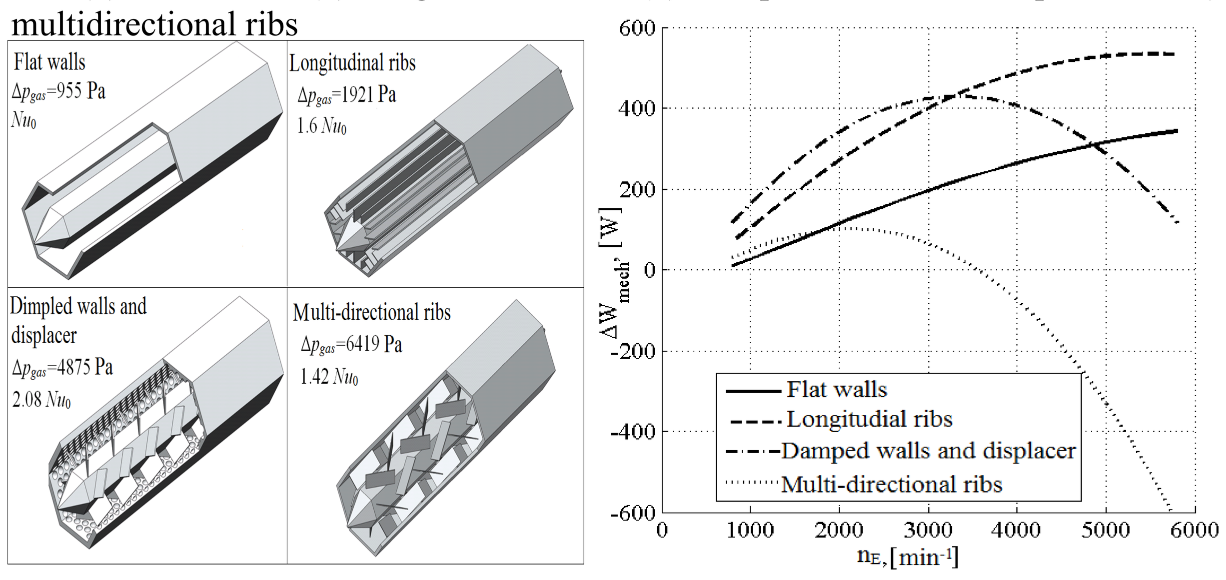
$k_{0,0}$	-4.35	W
$k_{1,0}$	-182e-5	W/Hz
$k_{0,1}$	0.205	W/Pa
$k_{2,0}$	0	W/Hz^2
$k_{1,1}$	-1.27e-5	W/Hz·Pa
$k_{0,2}$	3.33e-6	W/Pa^2





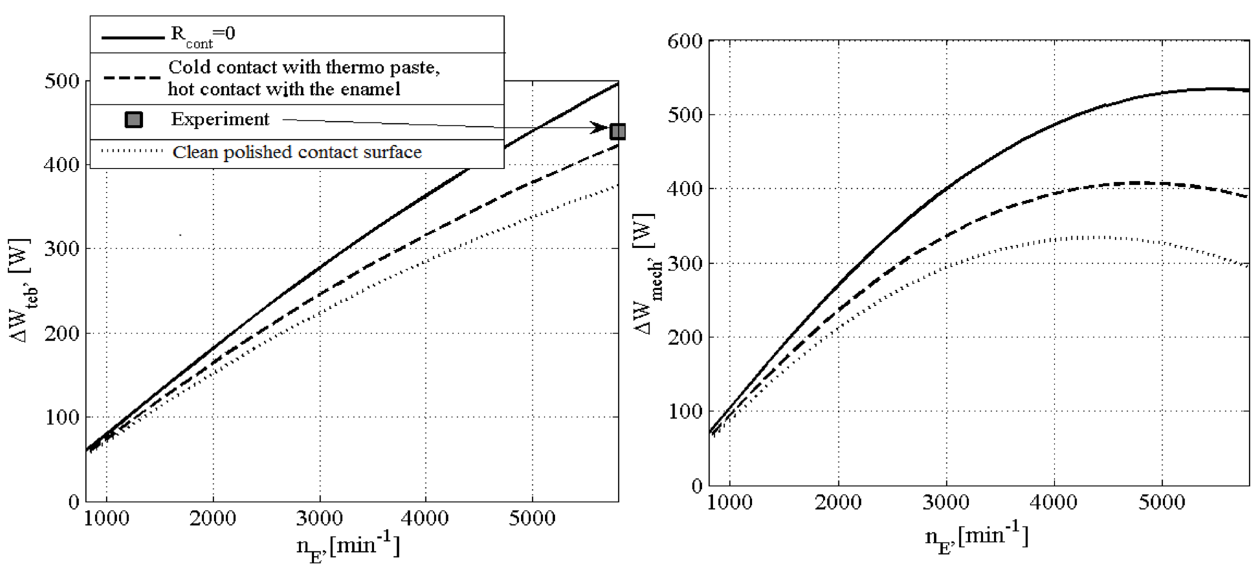
Modeling was held in **engine simulation tool "DIESEL-RK"** [http://www.diesel-rk.bmstu.ru]. Implemented a zero-dimensional multi-zone mathematical model to calculate the heat (for petrol engines) used the Vibe law. Calculations were carried out on the external velocity characteristic mode (at wide open throttle).

Total increase in the power on the shaft, ΔWmech, as a function of the rotational speed nE: *(1)* flat walls, *(2)* longitudinal ribs, *(3)* damped walls and displacer, and*(4)* multidirectional ribs



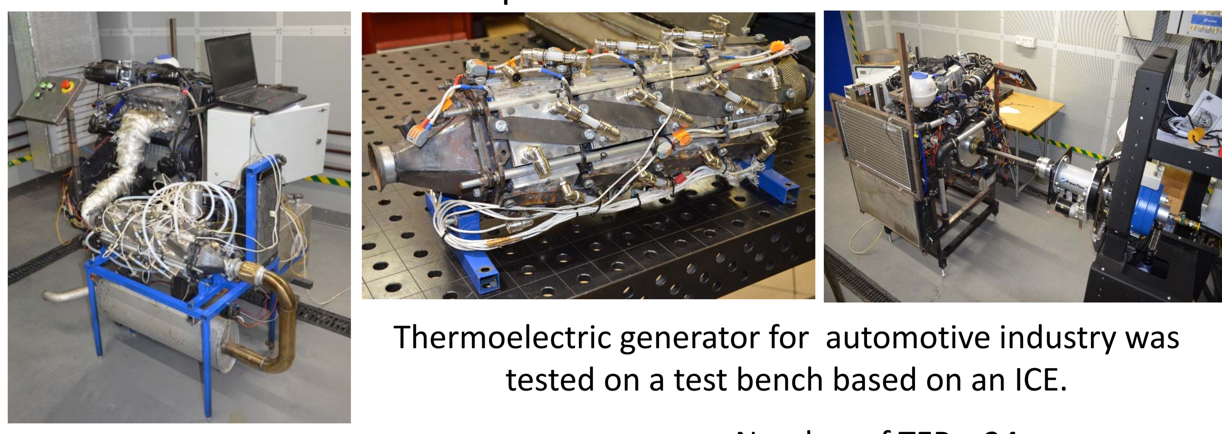
Influence of the contact thermal resistances on the *(a)* TEB power Wteb and *(b)* the increase in the ICE power ΔWmech:

(1) Rcont = 0, *(2)* cold contact with thermal paste and hot contact with enamel, and *(3)* clean polished contact surface; the experimental value is shown by a square.



Experiment

Experimental stand

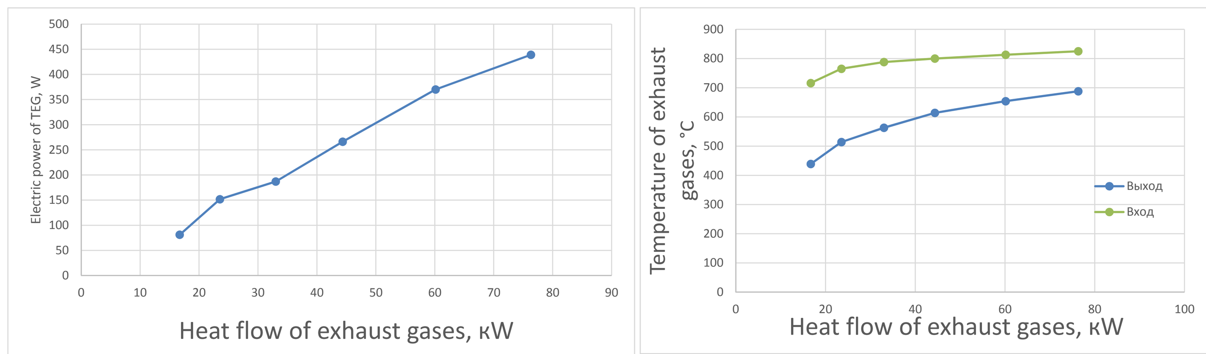


Thermoelectric generator for automotive industry was tested on a test bench based on an ICE.

- Engine power: 78 kW
- Exhaust gas temperature: 850°C
- Exhaust gas mass flow: 317 kg/hr
- Number of TEBs: 24
- TEG power: 450Вт

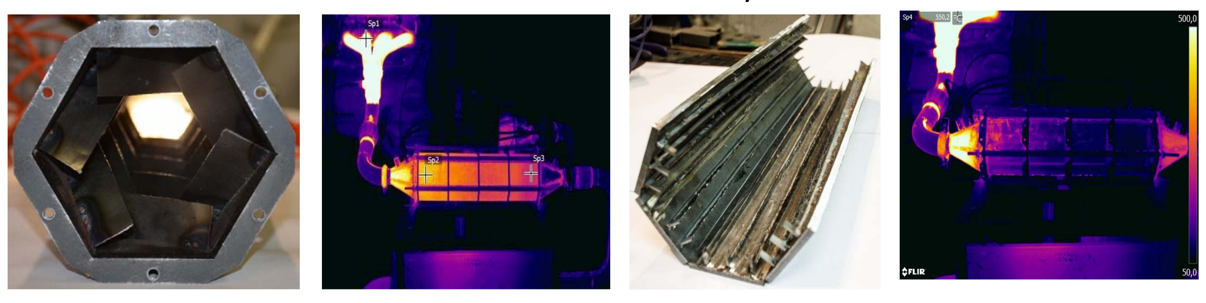
Supervisory control and data acquisition | TEG for 1 kW with 360 kW engine

Results for 450 TEG with 78 kW engine



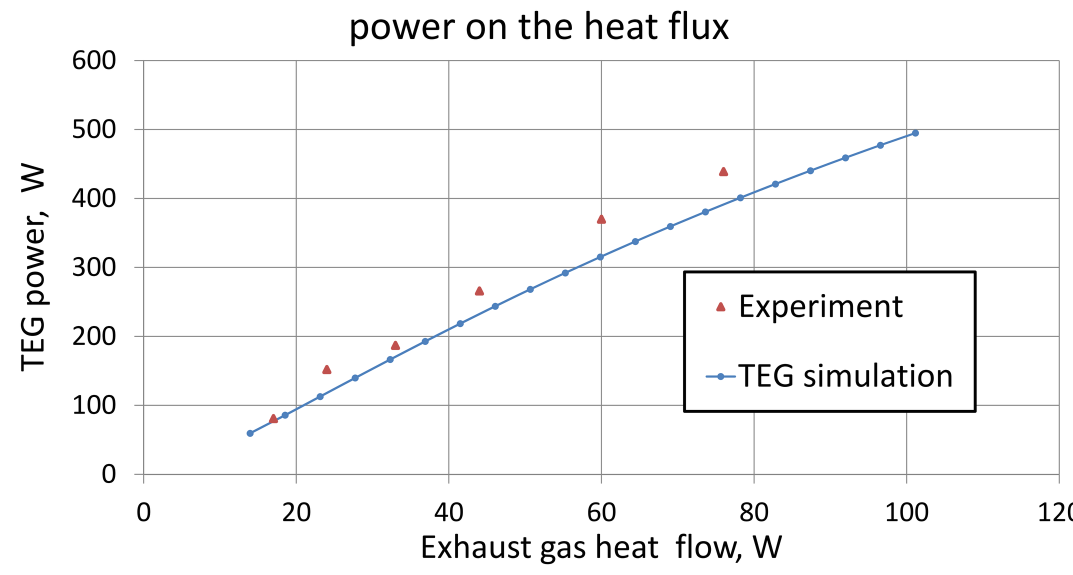
Different types of inner construction

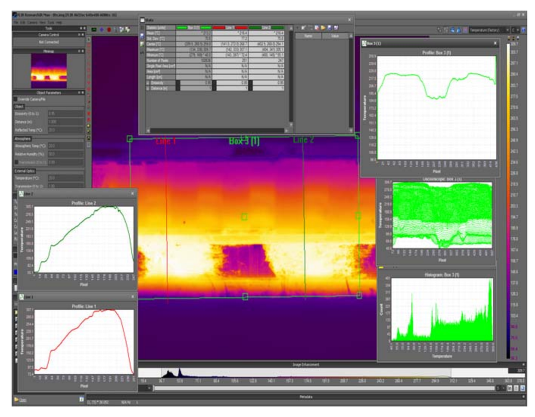
Tests of two different systems:



Blades inclined to the gas flow direction | Ribs parallel to the gas flow direction

Experimental and theoretical dependences of the generator power on the heat flux





Experimental evaluation of thermal resistances

R_{cont_hot}, K m^2 W^{-1}	Clean	9.96×10^{-4}
	With enamel instead of thermal paste	5.67×10^{-4}
R_{cont_cold}, K m^2 W^{-1}	Clean	11.7×10^{-4}
	With thermal paste	6.37×10^{-4}

CONCLUSION

- The efficiency of a thermoelectric generator largely determined by the design of the heat exchanger, so you must carefully choose the method of heat exchange.
- The most rational design which provide the highest ratio (Nu / Nu0) / (ξ / ξ0) is the design with - Ribs parallel to the gas flow direction and surface with pits. These structures are suitable for use in stationary plants and heavy transporting vehicles, since they can provide the greatest overall increasing of efficiency. Depending on the purpose of the thermoelectric generator it may be the use of other methods of enhancement of heat transfer.
- In the case of a thermoelectric generator for compact vehicles, such as motorcycles and cars, to provide reasonable efficiency with compact size and to reduce weight may be required structures, providing greater heat transition, even with larger gas-dynamic losses. In this case, the design can be modified to turbulator with pits and wave forming of the blades.
- It is desirable to develop a design of a TEG with variable internal finning to reduce the resistance at high exhaust velocities and increase the heat flux at small

CONCEPT