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Computer program for indicator diagram processing of the internal combustion engine

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Abstract. The article presents computer program for processing an indicator diagram of internal combustion engines developed by the author. The program input data are engine construction and operating parameters and cylinder pressure data array. The input data is saved to user files with *.txt and *.xls extensions. As a result of program execution, the following are calculated: engine indicator parameters; in cylinder working substance temperature; the rate of pressure increase; the current values of the heat-release and net heat-release and other quantities. The program is developed in a *Matlab* environment, compiled into an executable (*.exe) file and works in dialog mode. All calculations results are recorded in a custom file. This file is opened and saved with *Microsoft Excel*. The program is applicable by spark ignition and compression ignition engines working with: gasoline, LPG, CNG, diesel, diesel-LPG dual fuel, diesel-CNG dual fuel and diesel-hydrogen dual fuel.

1. Introduction

Internal combustion engine working cycle is referred with complicated and interconnected physical, chemical, thermo dynamical, gas dynamical and other processes. These processes are performed featuring extreme dynamic. Indicator diagram of internal combustion engine and its next mathematical processing gives the most complete and accurate quantitative assessment of engine process parameters. Internal combustion engine indicator diagram gives dependency of engine cylinder pressure – p_{cyl} upon cylinder volume – V_{cyl} or crankshaft angle – φ . Functions graphics $p_{cyl} = f(V_{cyl})$ and $p_{cyl} = f(\varphi)$ are called folded and expanded indicator diagram respectively. Engine indicator diagram is recorded with measurement complex which consists of sensors (cylinder pressure sensor, engine speed sensor, crankshaft position sensor); signal amplifiers; data acquisition system; data monitoring system.

Engine test bench laboratory system manufacturers (for example *AVL*, Austria) are offering computer-based systems for recording and processing of engine indicator diagram. Processing of indicator diagram in such systems is fully automated. Such systems have a high price. Furthermore the indicator diagram processing is based on engine operation with the main types of liquid or gaseous fuels. Thus obtained results are not quite correct when operating the engine on gas-diesel cycle. From other hand, research companies with lower financial capacities are developing their own systems for recording engine indicator diagrams [1-5]. These systems are equipped with sensors, amplifiers and measuring tools from different manufacturers. According to specific research purposes, computational programs for engine indicator diagram processing are developed [6-8].



2. Purpose of the article

According to upper text, purpose of current manuscript is to announce developed by the author computational program for processing of experimental obtained internal combustion engine indicator diagram.

3. Mathematical relations

The indicator diagram processing is carried out for the period during which the quantity of the working substance in the engine cylinder does not change, namely from the moment of closing of the inlet valve until the moment of opening of the exhaust valve. During this period the compression, combustion and expansion processes take place. The compression process starts from the moment the inlet valve is closed. The compression end and the start of combustion are determined by the first positive value of the heat-release rate – $dX/d\varphi$. The combustion process ends when the heat-release coefficient – X reaches 0,99 ($X = 0,99$). If, until the exhaust valve is opened, the heat-release coefficient is less than 0,99 ($X < 0,99$), the end of combustion is determined by the maximum value of the net heat-release coefficient – X_a^{max} . Further in text the working substance parameters at characteristic points of the indicator diagram are denoted by following indices: start of compression (inlet valve closes) – „a“; end of compression and start of burning – „c“; end of burning – „z“; end of extension (exhaust valve opens) – „b“.

During compression are calculated fresh medium temperature – T_{cyl} , K and middle polytropic index – n_l . Formulas known from thermodynamics are used:

$$T_{cyl} = \frac{p_{cyl} V_{cyl}}{m_{fm} \cdot R_{fm}}; \quad (1)$$

$$n_l = \frac{\lg p_c - \lg p_a}{\lg V_a - \lg V_c}, \quad (2)$$

where: p_{cyl} is current value of cylinder pressure, Pa; V_{cyl} – current value of cylinder volume, m³; m_{fm} – in cylinder fresh medium mass, kg; R_{fm} – fresh medium gas constant J/kg.K; p_a , p_c and V_a , V_c are pressure and cylinder volume respectively at compression start and compression end. During compression fresh medium gas constant does not change and is equal neither to that of air or to gas constant of air-fuel mixture.

Cylinder volume is calculated by well-known from internal combustion engine theory and design formula:

$$V_{cyl} = \frac{\pi D^2}{4} \left\{ \frac{S}{\varepsilon - 1} + \frac{S}{2} \left[(1 - \cos \varphi) + \frac{1}{\lambda} \left(1 - \sqrt{1 - \lambda^2 \cdot \sin^2 \varphi} \right) \right] \right\}, \quad (3)$$

where: D is cylinder bore, m; S – piston stroke, m; λ – ratio of connecting rod length to crank radius; ε – compression ratio; φ – crankshaft angle, rad.

According to engine type, fresh medium mass – m_{fm} is equal neither to cycle air mass – m_{air} (by compression ignition engines) or sum of cycle air mass and cycle fuel mass – m_{fuel} (by spark ignition engines and gas powered diesel engines). Cycle mass air and fuel are calculated by equation:

$$m_{air} (m_{fuel}) = \frac{G_{air} (G_{fuel}) \cdot \tau}{i \cdot 120 \cdot n}, \text{ kg/cycle}, \quad (4)$$

where: G_{air} and G_{fuel} are air and fuel consumption, kg/h; τ – engine strokes; i – number of engine cylinders; n – crankshaft speed, min⁻¹.

Indicator diagram processing during combustion and expansion is based on thermodynamics first law and is realized by method, published in [9-10]. The essence of methodology is to determine the heat-release rate. After that is calculating the in cylinder working substance temperature. During program developing differential equations suggested by R. M. Petrichenko are used:

$$\frac{dX}{d\varphi} = \frac{m_{ws} \cdot c_v \cdot T_{cyl}}{m_{fuel} \cdot H_u} \left(\frac{d \ln p_{cyl}}{d\varphi} + k \cdot \frac{d \ln V_{cyl}}{d\varphi} + \frac{1}{m_{wm} \cdot c_v \cdot T_{cyl}} \cdot \frac{dQ_w}{d\varphi} \right); \quad (5)$$

$$\frac{dT_{cyl}}{T_{cyl}} = \frac{1}{m_{wm} \cdot c_v \cdot T_{cyl}} (m_{fuel} \cdot H_u \cdot dX - dQ_w) - (k-1) \cdot \frac{dV_{cyl}}{V_{cyl}}, \quad (6)$$

where: m_{ws} , kg, c_v , J/kg.K and k are mass, volume specific heat capacity and adiabatic index of working substance respectively; H_u – fuel lower heating value, J/kg; $dQ_w/d\phi$ – heat lose rate to over piston space walls, J/deg. Differential equation from net heat-release rate – $dX_a/d\phi$ is the same at equation (5) without calculating heat loses, i.e. $dQ_w/d\phi = 0$.

The differential – dQ_w , is calculated from the equation:

$$dQ_w = \alpha_w \cdot F_{cyl} \cdot (T_{cyl} - T_w) \cdot dt = \alpha_w \cdot F_{cyl} \cdot (T_{cyl} - T_w) \cdot \frac{d\phi}{6n}, \quad (7)$$

where: α_w is convective heat transfer coefficient, $W/m^2.K$; F_{cyl} – over piston cylinder area, m^2 ; T_w – middle wall temperature, K. Convective heat transfer coefficient – α_w is given by *Woschni* formula [11]:

$$\alpha_w = 127,93 \cdot D^{-0,2} \cdot p_{cyl}^{0,8} \cdot W^{0,8} \cdot T_{cyl}^{-0,53}, \quad (8)$$

where: W is in cylinder working substance characteristic speed, calculated by [11].

Working substance during combustion is a gas mixture, consisting of fresh working mixture and burning gases. This mixture is on continuous change of its composition in proportion to burned fuel quantity, i.e. in proportion of heat-release coefficient. Thermodynamic properties of working substance during combustion (mass specific heat capacities by constant volume and constant pressure – c_v and c_p , gas constant R and adiabatic index k) are calculated based on gas mixture well known formulas:

$$c_v = \frac{m_{fm}}{m_{ws}} \cdot c_v^{fm} + \frac{m_{eg}}{m_{ws}} \cdot c_v^{eg}, \quad (9)$$

where: c_v , c_v^{fm} , c_v^{eg} and m_{ws} , m_{fm} , m_{eg} are volume specific heat capacities and mass of working substance, fresh working substance and burned gases.

When operating the engine with standard liquid fuels (petrol and diesel fuel) burned gases thermodynamic properties are defined from table data – [12], which depend on temperature and air-fuel ratio. When operating the engine on gas-diesel cycle, thermodynamic properties of exhaust gases are calculated depending on mass fraction of basic components [13], for example:

$$c_v = \sum_{i=1}^n m_i \cdot c_{vi}, \quad (10)$$

where m_i and c_{vi} are mass fraction and volume specific heat capacity of corresponding component. Mass fractions of exhaust gas components (carbon dioxide - CO_2 , carbon monoxide - CO , water vapor - H_2O , hydrocarbons H_nC_m , free oxygen - O_2 and nitrogen - N_2) are calculated depending of fuel elemental composition and air-fuel ratio – [12-13].

Middle polytrophic index during expansion is calculated by formula (2) as pressures and volumes in points a and c are replaced by these in z and b .

4. Description of the program

The computational program is developed in *Matlab* environment, compiled into executable file and works in dialog mode in the *Microsoft Command Prompt* – figure 1. The program consists of the following main modules: input data; calculation procedure; display and record results. Input module includes: engine geometric parameters; working parameters of engine; crankshaft angle and cylinder pressure data area. Engine geometric parameters are entered in user file *data_eng.xls* – figure 2. The user must enter the following data: cylinder bore D , m; piston stroke S , m; connecting rod length L , m; compression ratio ε ; engine stroke τ ; number of engine cylinders i ; valve timing. The following engine work parameters must be known for processing the indicator diagram: engine speed n , min^{-1} ; liquid fuel consumption G_{fuel} , kg/h; gas fuel consumption (only by gas powered spark ignition engines and diesel dual fuel engines) – G_{gas} , kg/h; air consumption G_{air} , kg/h; ignition angle θ , degree before TDC; diesel fuel injection duration ϕ_{inj} , crankshaft degree; middle cylinder wall temperature T_w , K. The

engine work parameters are entered in the user file *eng_work.xls* – figure 3. The crankshaft angle and cylinder pressure data are entered in a text file - *data_id.txt* – figure 4. The respective values must start from the top dead centre (TDC) at the inlet beginning (0 degree) and end one degree before the expansion ending (TDC), i.e. the indicator diagram data are in interval from 0 to 719 crankshaft degrees. After entering the input data, the user has to choose the engine duty cycle type. There are the following options: spark ignition engines working with gasoline, LPG, CNG and hydrogen, and compression ignition engines working with diesel or diesel-LPG dual fuel, diesel-CNG dual fuel and diesel-hydrogen dual fuel.

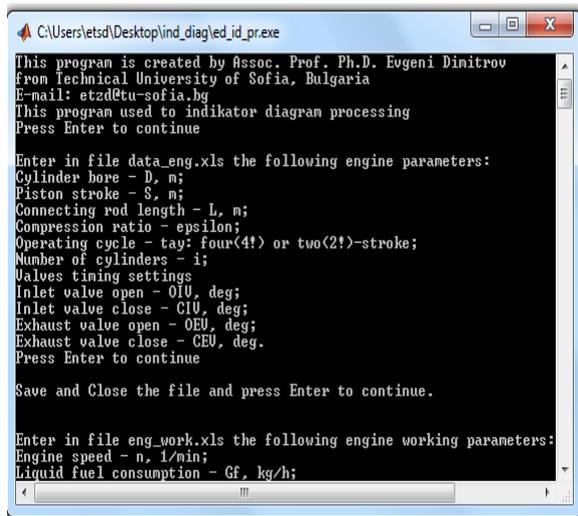


Figure 1. Main window of the program.

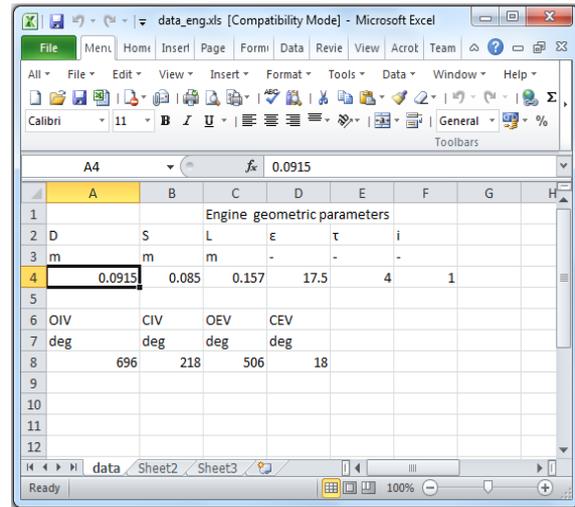


Figure 2. Entering engine geometric parameters.

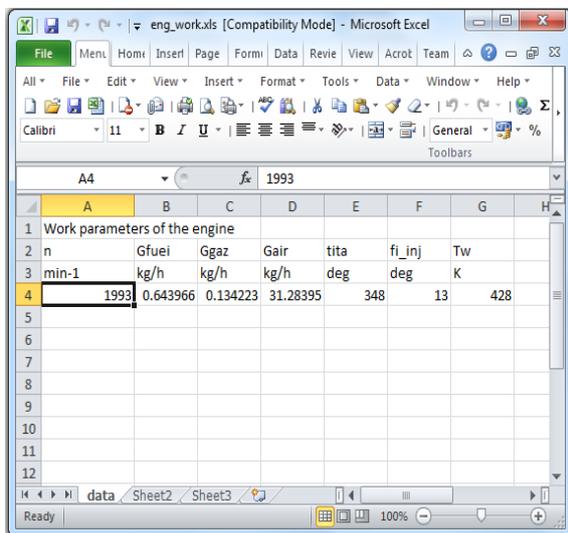


Figure 3. Entering engine work parameters.

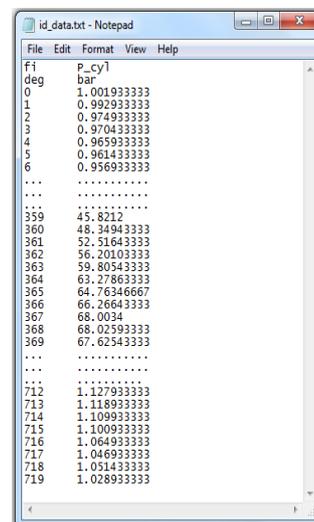


Figure 4. Entering crankshaft angle and cylinder pressure data.

The main part of the calculation procedure is cyclically repetitive mathematical and logical operations. The calculation cycle starts from inlet valve closing and continues until exhaust valve opening. At each step of the calculation, it is checked for the phase of the engine operating cycle. Then, step by step, the process-specific parameters are calculated. For example, during the combustion the following parameters are sequentially calculated: heat-release and net heat-release rate – $dX/d\phi$ and $dX_a/d\phi$; heat-release and net heat-release coefficient – X and X_a ; work substance temperature –

T_{cyl} ; heat losses – dQ_w and thermodynamic properties of the working substance. The thermodynamic properties of the work substance are calculated by subroutines called from the main program. The values of specific parameters and their corresponding crankshaft angles are determined during performance of the cycle, for example: maximum pressure – p_{max} and φ_{pmax} ; maximum temperature – T_{max} and φ_{Tmax} ; maximum pressure increase rate – $(dp/d\varphi)_{max}$ and $\varphi_{(dp/d\varphi)max}$; and others. The crankshaft angles for specific values of heat-release coefficient are also determined. The calculation results are presented (as graph forms) in separate windows – figure 5 to figure 8.

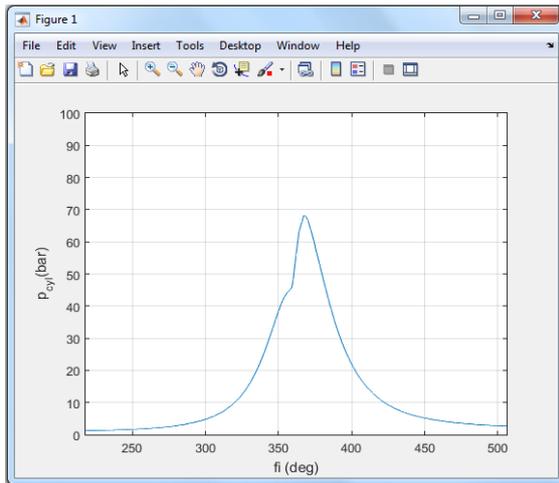


Figure 5. Cylinder pressure change depending on the crankshaft angle – $p_{cyl} = f(\varphi)$.

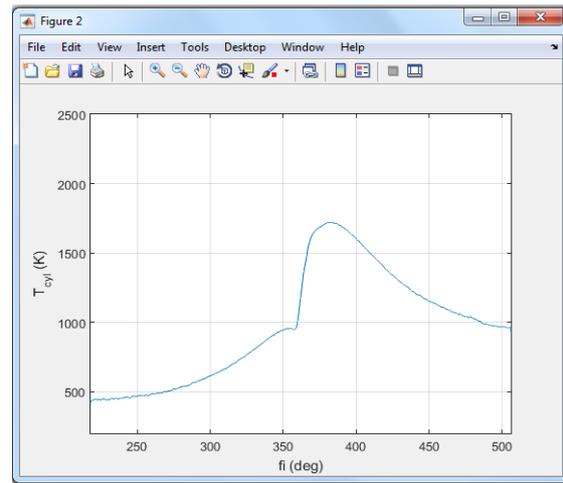


Figure 6. Cylinder temperature change depending on the crankshaft angle – $T_{cyl} = f(\varphi)$.

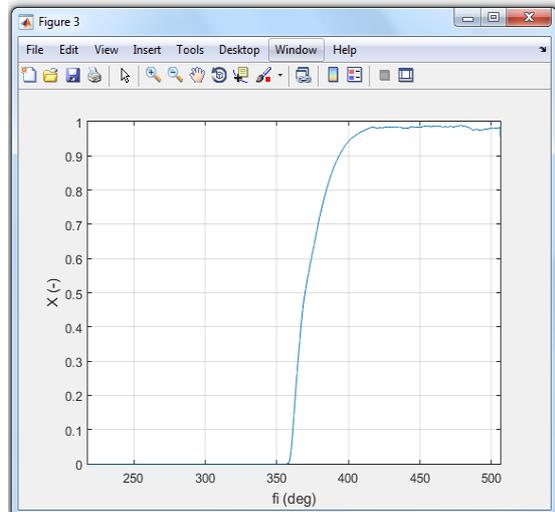


Figure 7. Change of heat-release coefficient depending on the crankshaft angle – $X = f(\varphi)$.

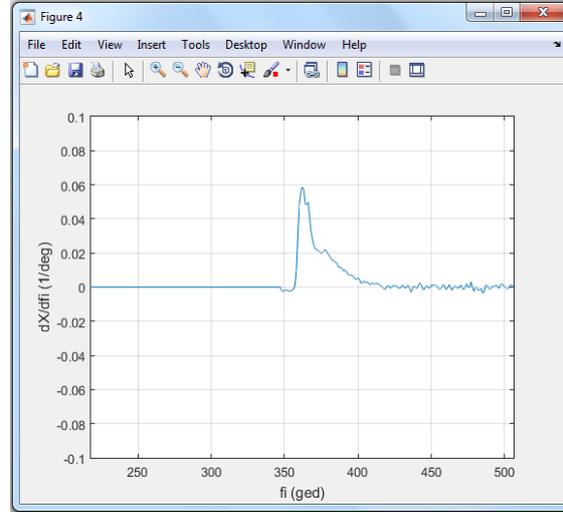


Figure 8. Change of heat-release rate depending on the crankshaft angle – $dX/d\varphi = f(\varphi)$.

Before starting the main cycle, are calculated the values of characteristic parameters and arrays: mean indicator pressure – p_i , middle polytropic index – n_i , current cylinder volume – V_{cyl} and its derivative – $dV_{cyl}/d\varphi$, pressure increase rate – $dp/d\varphi$ and others. Specific subroutines have been developed for some of the calculations.

After the calculations, all results (parameters and arrays) are recorded in a custom file *id_full.xls* – figure 9. This file is opened automatically. In order not to lose data by next running the program, the user must save the file *id_full.xls* under another name. After data saving, the program is automatically closes when the user presses a *Enter*.

Indicator diagram processing															
Engine geometric and work parameters															
S	L	ε	i	i*Vh	τ	n	θ	Tw	G _{air}	G _{fuel}	G _{gas}	K _{gas}			
mm	mm	-	-	dm ³	-	min ⁻¹	deg	K	kg/h	kg/h	kg/h	%			
85	157	17.5	1	0.558922	4	1993	348	428	31.28395	0.643966	0.134223	17.24817			
Data from the indicator diagram processing															
p _{cyl_max}	fi_p _{cyl_m}	T _{cyl_max}	fi_T _{cyl_m}	(dp/dfi) _m	fi_(dp/dfi)	(dx/dfi) _m	fi_(dx/dfi)	X _{pci_ma}	X _{end}	fi_X _{end}	X _{max}	fi_X _{max}	X _{a_max}	fi_X _{amax}	fi_burn pr n1
bar	bar	K	deg	bar/deg	deg	1/deg	deg	-	-	deg	-	deg	-	deg	deg
68.02593	368	1720.758	382	3.9258	361	0.058661	362	0.449591	0.988904	479	0.988904	479	0.854705	415	59 1.30376
Crankshaft angles for heat-release coefficient															
fi_X10	fi_X20	fi_X30	fi_X40	fi_X50	fi_X60	fi_X70	fi_X80	fi_X90	fi_X999	fi_X100					
deg	deg	deg	deg	deg	deg	deg	deg	deg	deg	deg					
361.1662	362.9147	364.7817	366.8272	369.6447	374.0128	378.8278	384.5301	393.3279	-	-					
Arrays of data															
P _{cyl}	dp/dfi	T _{cyl}	X	dX/dfi	Xa	dXa/dfi									
bar	bar/deg	K	-	1/deg	-	1/deg									
1.001933	-0.009	0	0	0	0	0									

Figure 9. Recording of data from indicator diagram processing.

5. Conclusion

The author is of the opinion that the presented program is fully functional and can be used both in the educational process and in the processing of experimental research results. The program is developed for non-commercial purpose and it is freely distributed.

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