Use of the graphical analytic methods of studying the combustion processes in the internal combustion engine combustion chamber on the basis of similarity criterion

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Abstract

The task of improving the economic and ecological parameters of the internal combustion engines remains topical within the frameworks of the modern engine-building technology. Since a combustion engine is a complex system combining such units as an intake manifold, combustion chamber, exhaust manifold, one of directions of the engine development is adjustment of the joint operation of its units. The specified adjustment should better be performed with the use of the so-called integral characteristics.

The author means under an integral characteristic the rating plate of a unit (engine) containing information about all the possible modes and conditions of its use, specifies the optimal operating range and indicates all the basic values of efficiency – reliability – environmental friendliness at each point of its field. As a rule, integral characteristics are multi-parametric. It is common practice to coordinate the field of such characteristic by similarity criteria determining the unit or engine behavior in whole.

Keywords: internal combustion engines, combustion processes, graphical analytic method

Introduction

Data on presence of a similar combustion chamber characteristic is not available. However, in the literature one may find graphical analytic constructions relating to the combustion processes that satisfy the requirements to the integral characteristics to a great extent.

Use of the graphical analytic methods of studying the combustion processes is quite common and, according to the literature data, has been performed for rather long time already. The two main reasons of the wide use of such methods may be mentioned:

A. The combustion process in contrast to, for example, hydrodynamic flotation processes is more complicated in essence. Beside the physical processes influencing the fuel burn-out in the form of molecular, turbulent and convective transfer also the processes of chemical transformation of the raw materials to the fuel oxidation products accompanied by liberation of heat take place simultaneously. At that the significant role belongs to the heat loss processes resulted in by radiation transport, dissociation of the combustion products that are peculiar to the combustion chambers only. Analytical description of the progress of such set of processes faces significant difficulties. At the same time there are no generally accepted models both for description of the turbulent heat-and-mass transfer and for the combustion process kinetics. In view of the above said, solution of the specific tasks is performed with the use of a significant number of assumptions that's why the results of solution may have exclusively qualitative character or even lead to wrong conclusions.

B. Graphical form of the process progress representation as compared to analytical one features a number of advantages. In this case it is possible to find a qualitative simultaneous solution of the processes in respect of which we only know their history; it is possible to find the joint solution for dependences that is difficult to be found in analytical form; it is possible to carry out analysis of the empirical dependences and experimental data. The obviousness and clarity of this method allow using it by analyzing the combustion processes behavior.

In view of the above-said, let's consider the existing cases graphical methods use by analyzing the combustion processes.

Methods

The classic study of the combustion processes by the analysis of which the graphical dependence was used is the fuel mixture thermal explosion suggested by N. N. Semenov [9].

The state of fuel mixture within a closed vessel was considered. It was characterized by average (in terms of capacity) temperature and concentration values. It was thought that the vessel containing the mixture gives up the heat released during the reaction to the environment the temperature of which equals T_O.

The analysis of the process of thermal self-ignition was performed in graphical form in the form of a *Q*-*T*—diagram: the temperature is plotted as abscissa, and the amount of heat released or discharged from the vessel per a unit of time – as ordinate (Fig.1).

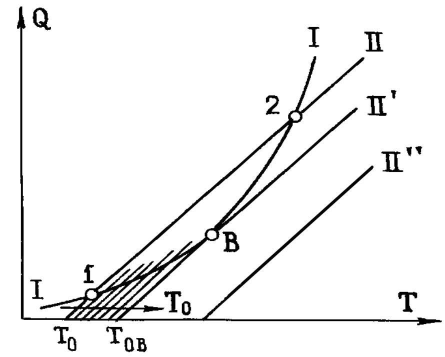

Fig. 1. Burn-out of fuel mixture in a closed vessel: I-heat release curve; II-heat transfer curve [2, 9].

The graphical analytic method used by the study of combustion issues allowed obtaining significant results. The presence of the particular critical phenomena (in the given case – ignition) during the exothermal process was shown. In terms of physics the critical condition characterizes the boundary mode beyond which the rate of heat liberation in the system always prevails over the discharge rate so the stationary process becomes impossible. The dynamic nature of the ignition phenomena has been identified. This feature is maintained upon the severest process conditions and is of great importance for the ignition theory in whole.

Another fundamental case of the graphical study of the combustion process can be found in the work of L. A. Vulis [2]: where the stationary mode of burning of a homogenous mixture in the adiabatic combustion chamber is considered (Fig. 2).

Just like in the previous task the solution of the process stationarity is found based on the condition of equality of the amounts of heat released and charged per unit volume of time and mass of the combustible mixture. The amount of the heat released is still determined by the chemical reaction behavior, however, at the same time the degree of the mixture burn-out is taken into account. The amount of heat discharged equals the withdrawal thereof from the

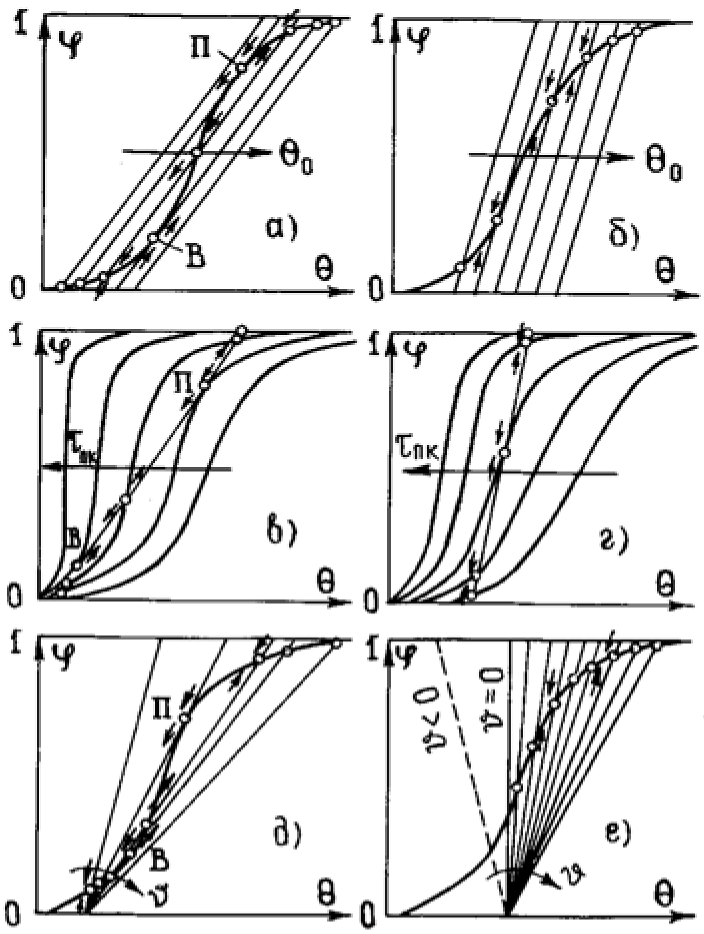

Fig. 2. Investigation of stationary modes: B-ignition; П-extinction; a and б-change of the initial temperature; в and г-change of the residence time; д and е-change of the heat value of mixture [2].

chamber by the heated combustion products. In contrast to the previous case where the quasi-stationary and non-stationary states have been considered it is referred to the possible stationary states of the system the duration of existence of which is not limited in principle. This determines the impossibility to consider the process within the $q-T$ - coordinates since with the fuel consumption the heat release curve will cross the inflection point.

Basic process equations:

$$Q_I = V \cdot q = \frac{C_O - C}{\tau.} \cdot q = k_o e^{-E/RT} \cdot C \cdot q \quad (1)$$

where V — reaction rate per 1 kg of mixture; q — heat value of mixture; C — relative weight concentration; E – energy of activation; k_0 – reaction rate constant; R – gas constant; T - temperature; τ_n – residence time.

Amount of heat carried out per a unit of time per 1 kg of mixture:

$$Q_{II} = \frac{c_p}{\tau_{\Pi}}\left(T - T_O\right), \quad (2)$$

where c_p – heat capacity at constant temperature.

The process stationarity condition is described by the equation:

$$Q_I = Q_{II}, \quad (3)$$

for identification of features thereof a graphical analytic study has been performed. In view of the general nature of analysis the dimensionless parameters have been used:

$\Theta = \dfrac{RT}{E}$ — non-dimensional temperature

$\vartheta = \dfrac{RqC_0}{Ec_P}$ — reduced heat value of mixture

$\varphi = 1 - \dfrac{C}{C_0}$ - combustion efficiency

The obtained graphical solutions and analytical dependences between particular parameters allowed to significantly deeper interpret the physical features of ignition and extinction — the critical modes of the stationary combustion process.

Besides, we were able to pass on to the specific computational study of the derived dependences. The graphical diagram in the $\varphi - \Theta$ — coordinates enabled it to represent the calculation results in dimensionless form (Fig.2).

The graphical analytic investigation of the “homogenous reactor” model gained further development due to the studies of J. Longwell [11], A. V. Talantov [10] describing the processes in a combustion chamber.

It was assumed that combustion is described by the single overall reaction where fuel and air react with a certain rate whereby the combustion products appear. It is suggested that the fuel and air supplied to the combustion zone are immediately mixed with all the substances that are present in the chamber and that the combustion products are removed from this zone with the temperature and composition identical to the temperature and composition in the chamber.

According to this model, the rate of reaction between the fuel and air may be derived from the material balance equation

$$\eta_c \varphi m_A = C_{cf} V T^{0,5} \exp\left(-\frac{E}{RT}\right) \rho^n x_F^m x_o^{\text{n-m}} \qquad (4)$$

here η_c — combustion efficiency, φ — equivalent proportion, m_A — mass flow rate, C_{cf} — collision factor, V — combustion zone volume, T — temperature, E – energy of activation, R – gas constant, ρ — density, x_F and x_o — fuel and oxygen concentration.

For the values m and n the values 1 and 2 have been used which corresponded to the second-order reaction. Having introduced these values and formulas for x_F and x_o to the material balance equation we obtained:

$$\frac{m_A}{V\rho^2} \sim \frac{1}{T^{1,5} \exp\left(E / RT\right)} \cdot \frac{\left(1-\eta_c\right)\left(1-\eta_c \varphi\right)}{\eta_c} \qquad (5)$$

The dependence of the heat release rate represented by the value in the right member of the last equation on the fuel combustion efficiency η_c is indicated in the Fig. 3.

Load intensity diagram

$\dfrac{m_A}{V\rho^2}$ or $\dfrac{m_A}{V\rho^{1,75}}$

in the Fig. 3 describes the amount of heat required for heating of the incoming mixture to the reactor temperature T. The point at which the load line crosses the heat release curve corresponds to the reactor (combustion chamber) operating mode. By increase in the fuel flow though the reactor the inclination of the load line increases until it ceases to cross the heat release curve which represents the flame blow-off.

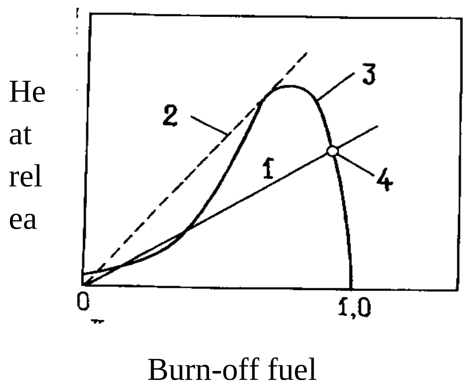

Fig. 3. Mechanism of burning and flame blow-off:

1- Load line;

2- Boundary load line;

3- Heat release line;

4- Set point

The given graphical method already significantly resembles the study of processes taking place in the real combustion chambers. It is also worth mentioning that it almost precedes the use of the similarity criteria in the graphical methods.

There is a number of research works [1, 4, 5] dedicated to the issues of simulating the processes in the combustion chambers of gas-turbine engines where the attempts have been made to find the complexes describing these processes and featuring the similarity criteria.

In order to solve this task the similarity theory is used that is based on the three fundamental physical laws: conservation of matter, energy and momentum. Mathematically these laws are represented by differential equations of the material and heat balance and viscous equation of motion.

In his study G. Damköhler works [3] has for the first time considered the equation data with regard to the processes of physic-chemical transformations and obtained beside the criteria of hydrodynamic and thermal similarity that have been known before the four new criteria (Damköhler's criteria):

$$D_I = \frac{a_i \omega \ell}{c_i \upsilon}; \quad D_{II} = \frac{a_i \omega \ell^2}{c_i D_i}; \; D_{III} = \frac{Q \omega \ell^2}{c_i \Theta \rho \upsilon}; \quad D_{IV} = \frac{Q \omega \ell^2}{\lambda \Theta}.$$

Here

c_i — concentration of i-th component; a_i — stoichiometric number of conversion; ω — chemical reaction rate; Q — heat of chemical reaction; D_i — coefficient of diffusion of i-th component; υ — flow rate; *l* – characteristic dimension; Θ - temperature; λ - thermal conductivity coefficient.

As G. K. Dyakonov has shown [5] that the specified criteria are not sufficient for identification of similarity of the physic-chemical processes in the most general case since the chemical reaction rate is the product of a certain mobile equilibrium of the conversion and exchange processes and the value of this rate is not covered by the similarity conditions.

G. K. Dyakonov has obtained the two new criteria that shall be taken into account by study of the combustion processes.

The first of them is the thermodynamic balance criterion:

$$Pa = \frac{k_2 / k_1}{a^{\alpha} b^{\beta} / \left(m^{\mu} n^{\eta}\right)} = \frac{u_{об}}{u_{пр}}$$

Here

k_1 and k_2 — constants of the forward and reverse process rates; a, b, m, n, — concentrations of substances A, B, M, N,…; $u_{пр}$ and $u_{об}$ — rates of the forward and reverse chemical reactions.

The physical significance of this criterion is the following: upon the thermo-chemical equilibrium *Pa=1* the net rate of the chemical reaction equals to zero.

The second criterion of G. K. Dyakonov is the contact number:

$$Ko = \frac{u_{пр}}{\omega}$$

Where ω — the net rate of the chemical reaction specified according to the concentration of the reaction product.

The physical significance of the contact number becomes apparent from the method of calculation thereof. May be written as:

$$Ko = \frac{k_1 a^{\alpha} \cdot b^{\beta}}{\partial c / \partial \tau}.$$

This relation is determined by the value:

$$k_1 \cdot c^{\Sigma\ \alpha - 1} \tau \sim \frac{\tau}{\tau_1},$$

where

c — concentration of the incoming substances; τ — residence time (conversion zone length); τ_1 — period of decay of the primary products of chemical reaction.

The last criterion plays a significant part in the study of the combustion processes in actual practice. The criterion which is similar in meaning was derived by V. F. Dumsky in his study [6] with regard to the flame stabilization tasks. It follows on the simple physical grounds that the contact (residence) time is proportional to the stabilizer size and inversely proportional to the flow rate. The time of the chemical reaction is specified according to the flame propagation theory (based on the assumption that the burning process corresponds to the ordinary laminar flame):

$$\tau_{Г} = \frac{a}{U_{Н}^2}$$

Where *a* — thermal conductivity coefficient; $U_{Н}$ — normal flame propagation rate.

Then the relation of times $\tau_{пр} / \tau_{Г}$ may be written as:

$$\tau_{пр} / \tau_{Г} \sim \frac{d_{ст} U_{Н}^2}{\omega a} = Mi\ .$$

V. F. Dumsky named this criterion the Michaelson's criterion. The fundamental character of this criterion allows using it not only within the flame stabilization theory but also by analyzing the process of the turbulent flame propagation [7].

With respect to the burners such criterion has been derived by I. I. Paleyev [8]. In cases when the combustion conditions approaches to the pure diffusion ones it can be suggested that the main factor influencing the combustion process is the mixing of fuel with oxidizer since the rate of chemical transformations is so high that it does not limit the combustion process intensity. In this case the main task of simulation is the investigation of the patterns of the gas flows mixing.

I. I. Paleyev suggested the following criteria:

$$\frac{\tau_{П}}{\tau_{Г}} \sim \frac{p^{n-1} d}{\omega}$$

where p — pressure; n — order of chemical reaction.

CONCLUSION

Results show that it makes sense to use the integral characteristic by analysis of operation of a combustion chamber both as an autonomous unit and as part of the internal combustion chamber. The absence of such characteristic creates certain difficulties by design and development of the combustion chambers and the internal combustion engines in whole. In this regard the further objective set – is to develop on the basis of the analytical and experimental research the concept, content and method of application of the integral characteristic of the internal combustion engine chamber.

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