STUDY OF THE INFLUENCE OF DIFFERENT FACTORS ON COMBUSTION PROCESSES (PART TWO)

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Abstract

The gas-phase occurs in homogeneous or heterogeneous form. In the first case the kinetics of chemical reactions controls processes of the combustion, in second, heterogeneous one - processes to run most slow down. For liquid fuels, decomposition processes of the liquid phase occur, that is processes vaporize of the fuel. Decomposition processes need a lot of heat, run slowly down than processes of the preparation of the mixture in gas phase of. The influence of the pressure on processes of the combustion of liquid fuels differs from the influence on the processes of the combustion of fuel gases. Pressure increasing decreases the intensity decomposition of the liquid phase. Flow of combustion gases intensifies combustion processes. Example-test results PIV velocity field, test results with LDV and PDPA are presented in the paper. The linear and volumetric distribution of the drop, and the Rosin – Rammler dependences as well as the course of the combustion process in the constant volume chamber are an object of the paper. The paper describes the mathematical model of the combustion process of the liquid fuel. Realized initial measurement of the boundary-layer thickness under model conditions with using of the LDV laser-equipment showed that the close relationship between the kinds of the boundary-layer existed, with its thickness and rate of the combustion of liquid fuels, washed with the gases stream. The pressure additionally bears on the velocity component of combustion rate, whereat this influence depends mostly from the kind of the fuel.

Keywords: combustion engines, combustion processes, fuel atomization, combustion modelling, laser research

1. Introduction

The gas-phase occurs in homogeneous or heterogeneous form. In the first case the kinetics of chemical reactions controls processes of the combustion, in second, heterogeneous one - processes to run most slow down. For liquid fuels, decomposition processes of the liquid phase occur, that is processes vaporize of the fuel. Decomposition processes need a lot of heat, run slowly down than processes of the preparation of the mixture in gas phase of. The influence of the pressure on processes of the combustion of liquid fuels differs from the influence on the processes of the combustion of fuel gases. Pressure increasing decreases the intensity decomposition of the liquid phase. Flow of combustion gases intensifies combustion processes.

2. Experimental set-up

Apparatus and Procedures

Researches were carried with LDV (the Laser Doppler Velocimeter) and PDPA (Phase Doppler Particle Analyzer) the laser and PIV (Particle the Image Velocimetry) equipment. The schema of the laser- measuring-system presents Fig. 1, and PIV - Fig. 2. View of the PIV system presents Fig. 3. Measurement LDV-PDPA realizes in the measuring-space which is intersection of two laser beams: zero Doppler. This space occurs in the area of optical focusing point of the laser-transmitter and has a shape of the rhomboid body.

The general PIV technique involves a multiple exposure photograph of a flow. A photographic image of the particles is obtained for a plane of particles, which has dimensions: the high of an illuminating laser sheet, the width of the image plane, and the thickness of the laser sheet. The light source is controlled to allow two exposures of the particle field to be recorded. The time between the exposures is controlled.
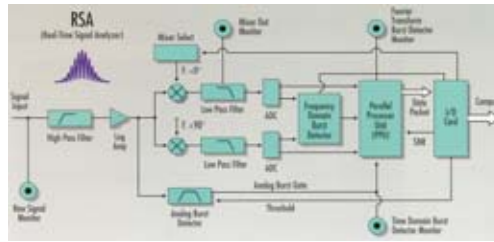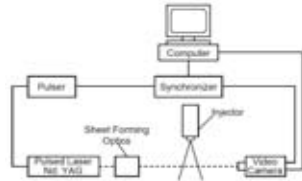
Fig. 1 Outline of LDV-PDPA laser system.

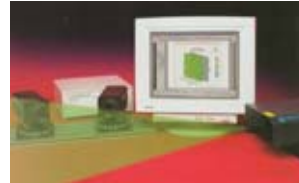*Fig. 2 Outline of PIV system*   *Fig. 3 View of PIV system*

The view of the laser with Bragg Cell presents Fig. 4, the view of the measuring-space and the test chamber presents Fig. 5.

Fig. 4 Laser and Bragg Cell equipment.   *Fig. 5 View of LDV-PDPA laser system with for research chamber.*

In research of the combustion processes speed film camera was used too.

3. Results and Discussion

Example-test results of the PIV velocity field present Fig. 6. Fig. 7 presents the lineal and volumetric drop distribution and the Rosin – Rammler dependences. Fig. 8 presents the course the combustion process in the constant volume chamber.
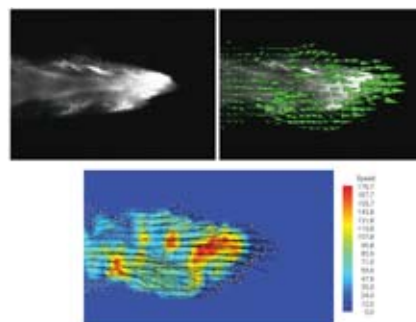

Fig. 6 PIV velocity field for liquid fuel spray

Fig. 9 presents the view of burnt strip of solid fuel flown with parallel stream of combustion gases. Fig. 10 presents cross-section of the boundary layer. Three kinds of the boundary layer: laminar, transient and turbulent layers are shown. Fig. 11 presents the comparison of burnt of stripe cross-section and the boundary-layer

4. Theoretical Model

Combustion rate can be indeed intensified at the occurring of turbulence stimulation of the gas stream of flowing fuel droplets.

The mass-rate of decomposition products stream for the liquid phase:
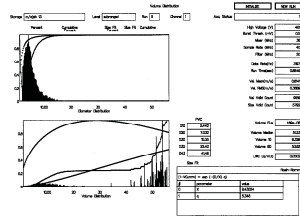
$$\dot{m} = \iiint_V \frac{d\beta}{dt} \rho_c dV.$$

(1)

Fig. 7. Linear, volumetric distribution and Rosin-Rammler dependence
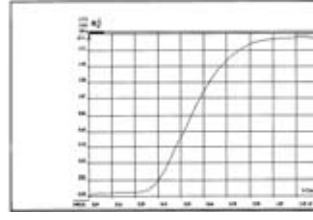
Fig. 8. Course of liquid fuel combustion process in constant volume chamber

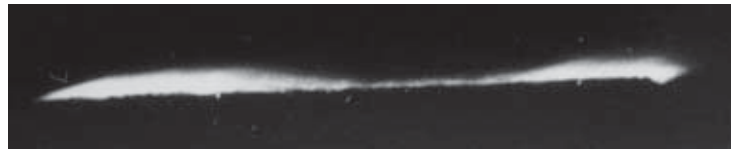*Fig. 9. Cross-section of burnt stripe of solid fuel*

Fig.10. Cross-section of the boundary layer for burnt stripe in Fig. 9
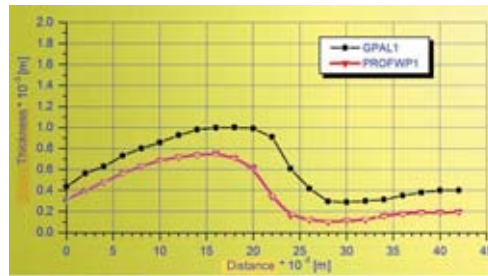

Fig. 11. The comparison of burnt of stripe cross-section and the boundary-layer

Equation of chemical reactions of the liquid phase:

$$\sum_{i=1}^{N^c} v_{i,k}^{'c} A_i^{'c} \Leftrightarrow \sum_{i=1}^{N^c} v_{i,k}^{''c} A_i^{''c}.$$

(2)

Rate of chemical reactions referred to volume unit of the liquid phase:

$$w_i^c = W_i^c \sum_{k=1}^{M^c} \left(v_{i,k}^{''c} - v_{i,k}^{'c}\right) \prod_{j=1}^{N^c} \left(\rho_c \frac{Y_i^c}{W_j^c}\right)^{v_{j,k}^{'c}} k_k^c(T).$$

(3)

where:

i=1... N^c,

k=1 ... M^c.

The mass-share of decomposition products of the "i" component:

$$\frac{d\beta_i}{dt} = \frac{w_i}{\rho_c}.$$

(4)

The temperature distribution in the liquid phase determines the equation of the energy conservation:

$$\rho_c c_c \left(\frac{\partial T}{\partial t} + \bar{v}_c \cdot grad\, T\right) = div(\lambda_c\, grad\, T) + \sum_{i=1}^{N^c} \sum_{k=1}^{M^c} \rho_{i,k}^c.$$

(5)

where:

$\rho_c = \rho_c\ [T,\ w_i\ (i=1,\ ...,\ N_c)],$
$c_c = c_c\ [T,\ w_i\ (i=1,\ ...,\ N_c)],$
$\lambda_c = \lambda_c\ [T,\ w_i\ (i=1,\ ...,\ N_c)].$

Constant reaction rate:

$$k_k^c = B_k^c exp\left(-\frac{E_c}{R_o T}\right).\tag{6}$$

Volumetric rate of heat source:

$$q_i^c = \sum_{k=1}^{M^c} q_{i,k}^c = w_i^c Q_i^c.\tag{7}$$

Equation of chemical reactions in gas phase:

$$\sum_{i=1}^{N^g} v_{i,k}^{'g} A_i^{'g} \Leftrightarrow \sum_{i=1}^{N^g} v_{i,k}^{''g} A_i^{''g}.\tag{8}$$

Equation of the chemical reactions rate in gas phase:

$$w_i^g = W_i^g \sum_{k=1}^{M^g} (v_{i,k}^{''g} - v_{i,k}^{'g}) \prod_{j=1}^{N^g} \left(\frac{p_g \frac{Y_j^g}{W_j^g}}{R_o \sum_{j=1}^{N^g}\frac{Y_j^g}{W_j^g}}\right)^{y_{j,k}^{g}} k_k^g(T).\tag{9}$$

Equation of mass conservation:

$$\frac{\partial \rho_g}{\partial t} + div(\rho_g \bar{v}_g) = 0.\tag{10}$$

Equation of momentum conservation:

$$\frac{\partial v_g}{\partial t} + \bar{v}_g \cdot grad\ \bar{v}_g = \overline{F}_g + \frac{1}{\rho_g} div\ \overline{\tau},\tag{11}$$

where: $\overline{\tau}$ − stress tensor.

$$\overline{F}_g = \sum_{i=1}^{N_g} Y_i^g f_i^g.\tag{12}$$

Equation of energy conservation:

$$\frac{\partial(\rho_g v_g)}{\partial t} + \bar{v}_g \cdot grad\ (\rho_g v_g) = div\left[(\lambda_g + \Delta\lambda_{gv}) gradT\right] - div\left[\rho_g \sum_{i=1}^{N_g} h_i^g Y_i^g(\bar{v}_{idif}^g + \Delta\bar{v}_{idifv}^g)\right] +$$
$$- div\left[R_o T \sum_{i=1}^{N^g} \sum_{j=1}^{N^g}\left\{\frac{X_j^g D_{T,j}^g}{W_i^g D_{i,j}^g}\left[\bar{v}_{idif}^g + \Delta\bar{v}_{idifv}^g - (\bar{v}_{jdif}^g + \Delta\bar{v}_{jdifv}^g)\right]\right\}\right] + div\overline{\overline{\tau}} \cdot \bar{v}_g + div p_g \bar{v}_g + \sum_{i=1}^{N^g} w_i^g Q_i^g.\tag{13}$$

Diffusion rate of the "i" component:

$$grad\ (X_i^g) = \sum_{j=1}^{N^g} \frac{X_i^g X_j^g}{D_{ij}}\left[\left(\bar{v}_{jdif}^g + \Delta\bar{v}_{jdifv}^g\right) - \left[\left(\bar{v}_{idif}^g + \Delta\bar{v}_{idifv}^g\right)\right]\right] + \left(Y_i^g - X_i^g\right)\frac{grad\ p_g}{p_g} +$$
$$+ \frac{\rho_g}{p_g}\sum_{j=1}^{N^g} Y_i^g Y_j^g\left(f_i^g - f_j^g\right) + \sum_{j=1}^{N^g}\frac{X_i X_j}{\rho_g D_{i,j}^g}\left(\frac{D_{T,j}^g}{Y_j^g} - \frac{D_{T,i}^g}{Y_i^g}\right)\frac{grad\ T}{T}.\tag{14}$$

Diffusion equation of the "i" component:

$$\frac{\partial(\rho_g Y_i^g)}{\partial t} + div(\rho_g Y_i^g \bar{v}_g) = -div\left[\rho_g Y_i^g(\bar{v}_{idif}^g + \Delta\bar{v}_{idifv}^g)\right] + w_i^g,\tag{15}$$

where:
$i=1,\ ...\ N^g,$

$\sum_{i=1}^{N^g} w_i^g = 0,$

$\sum_{i=1}^{N^g} div\left[\rho_g Y_i^g(\bar{v}_{idif}^g + \Delta\bar{v}_{idifv}^g)\right] = 0.$

Equation of state:

$$p_g = \rho_g R_o \sum_{i=1}^{N^g}\frac{Y_i^g}{W_i^g}.\tag{16}$$

Assuming the coordinate system connected with of the combustion surface we receive the dependence for concentration and temperature:

$$\frac{\partial \beta}{\partial t} = -r \frac{\partial \beta}{\partial \eta} , \tag{17}$$

$$\frac{\partial T}{\partial t} = -r \frac{\partial T}{\partial \eta} . \tag{18}$$

Then we receive:

$$-r \frac{\partial \beta}{\partial \eta} = (1-\beta) exp\left(-\frac{E_c}{R_o T}\right), \tag{19}$$

$$-g_c c_c r \frac{dT}{d\eta} = \lambda_c \frac{d^2 T}{d\eta^2} + \rho_c Q_c (1-\beta) B_c \, exp\left(-\frac{E_c}{R_o T}\right). \tag{20}$$

Boundary conditions:

$\eta = \infty, \qquad \beta = 0,$

$\eta = \infty, \qquad T = T_o,$

$\eta = 0, \qquad T = T_c,$

$\eta = 0, \qquad -\lambda_c \frac{dT}{d\eta}\Big|_w = q_g\Big|_w.$

The value of temperature of drop surface we determine using the following boundary condition on the border of liquid and of gas phases:

$\eta = 0, \; -\lambda_c \frac{dT}{d\eta}\Big|_w = q_g\Big|_w.$

Equation of concentration will take the following form:

$$\beta = 1 - exp\left(\frac{B_c}{r}\right)\int_\eta^\infty exp\left(\frac{E_c}{R_o T} d\eta\right). \tag{21}$$

Equation energy conservation is reduced to the temperature distribution equation:

$$T = T_o + \left\{T_w - T_o + \frac{Q_c}{c_s}\left[1 - \frac{E_s}{R_o T_w}\right]\right\} exp\left(-\frac{\rho_c c_c}{\lambda_c} r\eta\right) + -\frac{Q_c}{c_c}\left[1 - \frac{E_c}{R_o T}\left(1 - \frac{T_o}{T_w}\right)\right] exp\left[\left(-\frac{\rho_c c_c}{\lambda_c} r\eta\right)\frac{E_c}{R_o T_w}\left(1 - \frac{T_o}{T_w}\right)\right]. \tag{22}$$

Equation determining rate of mass stream of combustion products:

$$\dot{m} = \int_o^\infty (1-\beta) B_c \, exp\left(-\frac{E_c}{R_o T}\right)\rho_c A d\eta . \tag{23}$$

Rate of the heat flux referring to flow with substance supply will be smaller from rate of the heat flux relating to flow without such substance supply. This decreasing is relative to kind of gas stream flow which can be laminar, transient and turbulent.

Realized initial measurement of the thickness of the boundary-layer under conditions of model at using of the LDV laser-apparatus showed that the close relationship between the thickness of the boundary-layer and rate of combustion of liquid fuels with the gas stream of flowing fuel droplets existed.

Conclusions

From realized research and on the ground worked out theoretical model following conclusions can be formulated:

- Combustion rate at occurrence of convection, the tangent component of velocity of gases for liquid fuels changes processes of the combustion of these fuels.
- Increasing velocity of the stream always increases combustion rate, whereat kind of influence is relative to kind flow gas (laminar, transient, turbulent).
- The pressure influences additionally on the rate of velocity component of the combustion, whereat this influence depends mostly from the kind of the fuel.
- Increasing of pressure increases the rate of velocity component of the combustion, however with reference to some fuels can follow the lack of the influence velocity of gases or even reduction of combustion rate with the pressure increasing.

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List of major symbols

A'_i - substrates,

A''_i - reaction products,

B_k - frequency factor of „k" reaction in the Arrhenius equation,

c_{pg} - specific heat of gases at constant pressure,

c_c - specific heat of fuel,

$\dot{m}$ - mass rate of stream of products of reaction decomposition of liquid phase,

V - volume of heated zone,

$\bar{v}_g$ - vector of velocity of stream of combustion gases,

$\bar{v}_c$ - vector rate of displacement of phase border

$\bar{v}_{idyf}$ - vector of rate of diffusion of the "i" component,

W_i - molecular mass the "i" component,

w_i - mass-rate of reaction of the "i" component referred to volume unit,

X_i - molar share of the "i" component,

Y_i - mass share of the "i" component,

x,y,z - coordinates in fixed system,

α_x - local coefficient of heat transfer,

β - mass share of decomposition products of liquid phase,

Δq_{gx} - increment of the rate of heat flux supply to liquid phase caused flow stream of combustion gases,

$\Delta \bar{v}_{idyf}$ - increment of vector of diffusion rate of the "i" component caused flow of gas stream,

$\Delta \lambda_{vg}$ - increment of coefficient of heat conductivity caused flow of gas stream,

$\Delta \mu_{vg}$ - increment of coefficient of dynamic viscosity caused flow of gas stream,

ξ, η, ζ - coordinate in movement system connected with combustion surface (in this: η normal to combustion surface).

Index marks: ' - refers to substrates, " - refers to reaction products, g - refers to gas phase, c - refers to liquid phase.