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Theoretical and experimental investigations of the interaction of hot gases with liquid in closed volume

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ABSTRACT

Analytical and physical models of gasification for model liquid fuels are developed. Numerical and experimental modeling of heat and mass transfer processes were completed with convective and irradiative heat exchange during hot gas flow (heat carrier) into the closed volume with the residual liquid. The heat carrier gas parameters were the following: temperature of the heat carrier, 373 ± 2 K; temperature of the surroundings, 291 ± 2 K; and flow rate of the heat carrier, 300 l/min.

1. Introduction

Extraction of energetic resources from liquid rocket fuel debris in the tanks of the rocket stages in a developing active deorbiting system of the separating parts of rocket stages is based on the gasification of the fuel debris in the tanks and collecting the gasification products into a special rocket engine [1]. For investigating the process of gasification, analytical and physical modeling of the process is performed using an experimental model bench (EMB). The EMB parameters were chosen from similarity theory after an analysis of the real process that will occur in the fuel tanks of the separated parts of a rocket during heat carrier flow for different parameters [2–5].

Analytical modeling of the gasification process for the above-described stage is considered to be a concentrated model based on the heat balance method. This model, compared to the distributed model based on the Navier–Stokes system of equations, imposes fewer requirements on the performance of the PC, thus enabling results in less time as well as the use of the results of physical modeling during the integration of the equations of the model. However, correct use of this model is connected with the requirement to make some assumptions.

Analysis of the main problem indicated that the main branch of the investigation of the processes of liquid evaporation involves an investigation of the heat and mass transfer of liquid droplets that move in the flow of hot gases as well as the cooling of the gas flow via inletting the liquid [6]. For example, in paper [7], the process of heating the droplet to the equilibrium temperature of evaporation and the connections among the heating time, the temperature, and the size of the droplet was investigated. In work [8], the model of the mixture and the evaporation droplets of the fuel is discussed, based on the distributed numeric modeling of the field of the evaporated fuel concentration. In paper [9], numeric research of liquid droplet evaporation in a heated gas is described, based on the concentrated model; in addition, experimental research to investigate analytical modeling is described. In work [10,11], an analytical model of the non-equilibrium evaporation of liquid droplets by using the Navier–Stokes system of equations is discussed. Numerical simulations of liquid droplet combustion in turbulent flows of gaseous oxidant are described in [12–14]. The equilibrium and non-equilibrium boundary conditions on the

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surface of a burning droplet are considered in [15–17]. The peculiarities of over-expanded jet flows in vacuum accounting for possible chemical reactions are investigated in [18–21].

In the present study, a method to place the boundary conditions for each evaporating spherical droplet temperature distribution in the analyzed volume was developed by means of integrating the closed system of differential equations using the ANSYS software package.

2. Problem definition

The main aims of the investigation are:

- development of a concentrated model of the evaporation process in the closed volume of the EMB, including the film bordering conditions of the liquid and the temperature rate of the primary participants of heat exchange (gas, liquid, EMB walls, plate, and heat carrier);
- development of the physical model based on the available experimental stand [22];
- implementing the physical model, including defining the parameters of the physical model that satisfy the assumptions and best match the results of analytical modeling.

Assumptions accepted during the development of the analytical model:

1. An empirical formula is used for calculating the partial saturated pressure of the evaporated liquid (humidity) [23].
2. The temperature of the EMB walls (metal and glass), the gas in the EMB volume, and the liquid on the plate are in equilibrium for each participant of the heat exchange, that is, the absence of a temperature gradient.
3. The thermodynamic influence (convective and irradiative heat exchange) on the liquid based on the flow of hot gases (air) next to the heat carrier (HC) on the surface of the liquid placed inside the EMB without chemical reaction.
4. An acceptable pressure and temperature of the HC and the mass flow rate is detected from the similarity theory for boundary conditions for the strength of EMB construction and the assumptions made during analytical modeling.
5. During evaporation, the assumed "frozen" condition of the liquid means that the station is held fixed without any fluctuation of the free surface of the liquid [3].
6. The blackness rates of all of the participants of heat exchange (HC, gas mixture, liquid, plate, and walls) are constant.
7. For EMB, there are heat flows between the walls of the volume and the liquid because the liquid is placed on the plate and plate is mounted on thermal isolators.
8. The heat exchange coefficients from HC to the gas α_{HC}=const and from the gas to another participant of heat exchange α_G=const are constant and equal during the entire time of the process and are obtained from experiments.
9. The HC flow field distribution in the EMB for estimating the heat exchange coefficients is taken from a calculation using the program pack ANSYS.

3. Analytical model

The foundation for the analytical model was taken from the heat balance method [24].

Fig. 1 shows the distribution of heat flows inside the EMB.

The heat balance equation has the following form:

$$Q_{in} = Q_{heat} + Q_{out}, \tag{1}$$

where Q_{in} is heat energy from the heat carrier; $Q_{heat} = Q_{gas} + Q_{liq} + Q_{pl} + Q_{wall}$ is heat energy consumed for heating the participants of heat exchange (gas, liquid, plate for liquid, EMB steel and glass walls); and Q_{out} is heat energy out of the EMB.

These are the main equations for determining the changes of the internal energy for each of the participants inside the EMB.

3.1. Gas inside the EMB

The gas inside the EMB is the main element for carrying heat energy from the HC to the participants of the heat exchange (Fig. 1). The gas internal energy change has the following form:

$$dU_{gas} = dQ_{conv\ g-HC} + dQ_{rad\ g-HC} - dQ_{conv\ i} - dQ_{rad\ i} + i_{ev}\dot{m}_{ev}d\tau, \tag{2}$$

where U_{gas} is internal energy of gas; $Q_{conv\ g-HC}$ is the convective part of the heat exchange between the gas and the HC; $Q_{rad\ g-HC}$ is the irradiative part of the heat exchange; $Q_{conv\ i}$, $Q_{rad\ i}$ are the convective and irradiative parts of the heat exchange between the gas and another participant of the heat exchange; $i_{ev}\dot{m}_{ev}d\tau$ is the amount of heat energy transferred from the $\dot{m}_{ev}d\tau$ to the gas; and i_{ev} is evaporated liquid enthalpy.

3.2. Liquid on the plate

Liquid evaporates from the plate due to heating via the hot gas flow and from the plate on which it lies (Fig. 2).

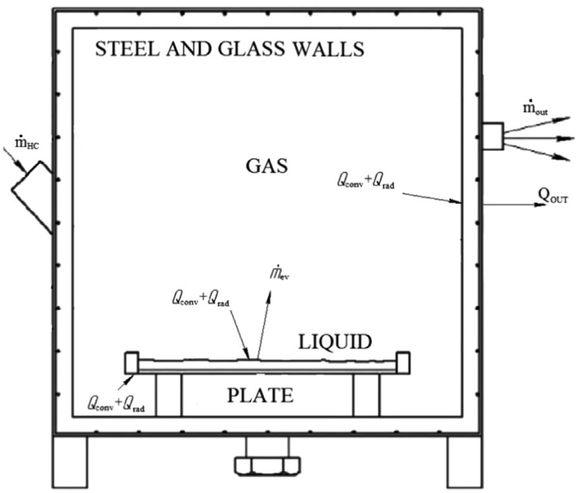

Fig. 1. Participants of the heat exchange process: gas, liquid, plate, EMB steel and glass walls.