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Thermal state calculation of chamber in small thrust liquid rocket engine for steady state pulsed mode

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Abstract This paper presents a method of thermal state calculation of combustion chamber in small thrust liquid rocket engine. The goal is to predict the thermal state of chamber wall by using basic parameters of engine: thrust level, propellants, chamber pressure, injection pattern, film cooling parameters, material of wall and their coating, etc. The difficulties in modeling the startup and shutdown processes of thrusters lie in the fact that there are the conjugated physical processes occurring at various parameters for non-design conditions. A mathematical model to predict the thermal state of the combustion chamber for different engine operation modes is developed. To simulate the startup and shutdown processes, a quasi-steady approach is applied by replacing the transient process with time-variant operating parameters of steady-state processes. The mathematical model is based on several principles and data commonly used for heat transfer modeling: geometry of flow part, gas dynamics of flow, thermodynamics of propellants and combustion spices, convective and radiation heat flows, conjugated heat transfer between hot gas and wall, and transient approach for calculation of thermal state of construction. Calculations of the thermal state of the combustion chamber in single-turn-on mode show good convergence with the experimental results. The results of pulsed modes indicate a large temperature gradient on the internal wall surface of the chamber between pulses and the thermal state of the wall strongly depends on the pulse duration and the interval.

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1. Introduction

Thrusters are used as the executive devices of the control system for spacecraft's angular position. There is development mainly with the radiation cooling system, so the question of assessing the thermal state of such an engine becomes very

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important. Pulsed mode is the main operation mode of the thrusters when it is used as an executive element. In Ref. 1, the requirements to the executive thrusters of control system, and the classification of operating modes, taking into account the thermal effect of engine wall heating, are considered. In many respects, the efficiency of the engine in the pulsed mode determines the quality of the operation and the lifetime of the entire spacecraft.[2] An big issue for the developer of thrusters is to ensure the permissible thermal state of the wall in each of its operation modes.

An analysis of the thermal state of the combustion chamber, operating on a pulsed operating mode, is a rather difficult task to calculate. The greatest difficulty is the simulation of unsteady processes during engine startup and shutdown.[3,4] This is due to the complex thermochemical processes of conversion of fuel into combustion products, and the hydrodynamics of the flow under the non-calculated operating conditions of the injectors when the pressure in the combustion chamber is absent. Models for calculating processes in chamber at unsteady regimes are based on empirical relationships obtained during experimental engine processing. Mathematical models of the engine operation in the pulsed modes are compiled, and the thermal characteristics of the considered engines are shown.[5,6] The availability of reliable experimental data on intra chamber processes in the modes of filling and emptying the mixing head and chamber is the key to adequate modeling for unstable operation modes of engine.

The difficulty in calculating the unsteady regime makes it necessary to use a quasi-stationary method when unsteady operating modes of the engine (startup and shutdown) are replaced by a set of stationary steady-state regimes with intermediate constant parameters of the working process in the combustion chamber.[7,8]

Theoretical modeling of steady pulsed operating modes of the engine, when the influence of unsteady processes is small, is possible without involving a large number of experimental data, but with subsequent verification of the results obtained. The complexity of such calculations is as follows:

(1) Use a large number of design relationships describing the physical processes occurring in the engine;
(2) Use a large amount of information of a thermodynamic database for various engine operating modes, taking into account the distribution of the component ratio in the cross section of the chamber, including film cooling and near wall layers;
(3) Develop a software program for calculating nonstationary thermal processes in the pulsed mode of operation of the engine.

Despite the large number of works devoted to the prediction of the thermal state of the combustion chamber wall, the engineer sometimes needs a simple fast 2D tool which in the early stages of design would allow calculating and comparing engine parameters without hardware producing, without performing CFD calculations, because the exact geometry has not yet been determined.

The prediction of the thermal state of the combustion chamber wall in pulsed operating modes allows analysis and optimization of engine design parameters during the development and testing phase.[9,10]

The purpose of the work is, based on the refined mathematical model, to calculate the thermal state of the thrusters at the steady pulse-operating mode.

2. Physical processes in combustion chamber of thrusters working at a single pulse

The processes in the engine with a single pulse are represented in the following order: after the electric command signal is applied, the process of opening the valves starts with a certain delay, the components enter the chamber, and their ignition and pressure increase in the combustion chamber. Simultaneously, the beginning of the pressure up, the process of the outflow of the vapor-gas phase, and then that of the combustion products from the engine nozzle occur. When the gas moves along the wall of the combustion chamber, the boundary layers on the wall of the chamber and the nozzle increase. Consequently, when the pressure in the chamber changes, the interaction of the gas flow with the wall leads to the formation of an unsteady boundary layer, through which the heat transfer process from the gas to the wall takes place. After the pressure becomes steady state, the boundary layer stabilizes according to its dynamic parameters, because the core of the flow becomes stable and the gas parameters in the core of the flow can be assumed to be stationary.

In view of the large thermal capacity and the thermal inertia of the combustion chamber wall, its temperature will vary. Because of the interaction of the boundary layer with the wall, the parameters of the boundary layer will change, as well as the heat flux to the wall. Thus, despite the stabilization of the flow in the core of the flow, stabilization of the boundary layer does not occur. The nonstationary process of the heat transfer process will take place until heat flux from products of combustion to wall will equal heat flux removed from the walls by heat radiation processes into space and insignificantly heat dissipation to the mixing head, valve assembly and the engine attachment points. Because heat radiation process will play an appreciable role in the heat balance only at high temperatures, the time to enter the stationary thermal state is comparatively large. Therefore, if the pulse duration is small, the heat transfer process will be nonstationary, even in the absence of stationary parameters of the working process in the combustion chamber.

After switching off the fuel supply and the pressure decrease in the chamber, the process of engine cooling due to radiation begins. If the interval time between the pulses is large, the temperature of the chamber and the pressure become equal to the temperature and pressure of the external conditions. In this case, the next pulse starts with the parameters corresponding to the external parameters. In this case, the effect of the previous pulse on the subsequent pulse does not occur – the engine operates in the mode of single or disconnected pulses. If the interval time between pulses is small, the next pulse starts at a chamber temperature different from the ambient temperature, in which case the effect of the engine operation in the previous cycle on the initial conditions of the next pulse will be affected. This will be the mode of operation with temperature-related pulses. If during a single pulse, the wall temperature has time to stabilize for a sufficiently long time – this will be a continuous stationary mode of operation.