Acta Astronautica 120 (2016) 129–137

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Invited Paper

Material combustion in oxidant flows: Self-similar solutions

V.V. Tyurenkova [a,b,*], M.N. Smirnova [b,c]

[a] Scientific Research Institute for System Studies of the Russian Academy of Sciences, 36-1 Nakhimovskiy pr., Moscow 117218, Russia
[b] Moscow M.V. Lomonosov State University, Leninskie Gory 1, Moscow 119992, Russia
[c] Saint Petersburg State Polytechnical University, 29 Politechnicheskaya Str., St. Petersburg 195251, Russia

ARTICLE INFO

Article history:
Received 17 September 2015
Accepted 25 November 2015
Available online 17 December 2015

Keywords:
Surface
Burning
Diffusion
Flame
Turbulence
Regression rate

ABSTRACT

The paper presents exact solution for the problem of condensed material surface burning in a flow of oxidant in the case of steady flame over fuel layer. The solution is obtained within the frame of assumption of fuel gasification and gas phase chemical reacting in a diffusion flame. The regression rate of the material surface in the turbulent and laminar flow regimes is studied. The zones corresponding to kinetic and diffusion regime are determined.

© 2015 IAA. Published by Elsevier Ltd. All rights reserved.

1. Introduction

The problems of blast and fire safety of flight vehicles are on top of current needs [1–3].

Boundary layers with chemical reactions in the course of condensed fuel burning in an oxidant gas flow occur in investigations of various processes, for example: burning of fuel in hybrid engines; interaction of hypersonic flying vehicles with the atmosphere; exo- and endothermic reactions in chemical engineering; spreading of flame over the fuel surface, the origination of explosions and the propagation of detonation in unmixed two-phase systems of the gas-film type [4,5]. For all of the above processes it is necessary to calculate the heat and mass transfer between a chemically reacting gas boundary layer and a reacting, melting, subliming, or otherwise destructing, surface. The methods of investigations in this field are very complicated, because the motion of a gas is governed not only by force and temperature fields but also by chemical processes depending in turn on velocity and temperature fields. This requires a conjugate solution of dynamic, thermal and diffusional problems with allowance for the equations of chemical kinetics, multicomponent diffusion and variability of thermophysical properties of a medium with distributed parameters. The process incorporates the thermochemical destruction of the surface when vapors of fuel substances, comprising the surface material, diffuse into a boundary layer and react chemically with the external flow [6–9].

2. Mathematical problem statement

The present work investigates the burning of the flat surface of fuel in an oxidant flow in the absence of an axial pressure gradient. The problem is solved within the framework of the assumptions of the laminar boundary-layer theory. Near the fuel surface in the gas, the boundary layer develops in the interior of which there proceed chemical reactions between the fuel vapors and the oxidant. Since these are exothermic reactions, energy is given up by the boundary layer in the gas. The heat from the heated gas transfers to the fuel layer which, having evaporated, gains access, as a result of diffusion, the boundary layer, where it enters into reaction with the oxidant. As a result of continuous inflow of heat from

* Corresponding author at: Scientific Research Institute for System Studies of the Russian Academy of Sciences, 36-1 Nakhimovskiy pr., Moscow 117218, Russia. Tel.: +79166236736.
E-mail address: tyurenkova.v.v@yandex.ru (V.V. Tyurenkova).

http://dx.doi.org/10.1016/j.actaastro.2015.11.033
0094-5765/© 2015 IAA. Published by Elsevier Ltd. All rights reserved.

the gas phase, the fuel becomes warmed up and a temperature boundary layer develops near the phase interface.

The solution of the problem will be based on the concept of diffusion flame and will use analytical research methodology developed in [10–12]. Contrary to symmetric problems solved in [10–12] the present problem statement will differ greatly by incorporating the flow dynamics in the frame of boundary layer approximation, and accounting for fuel heating dynamics on moving from the flame tip. In solving the problem it will be assumed that in the course of chemical transformations the reagents in the reaction zone are interrelated as

$$\sum_{i=1}^{N} m_i \nu_i' = \sum_{i=1}^{N} m_i \nu_i'' \tag{1}$$

Where ν_i', ν_i'' are the stoichiometric coefficients of the ith components before and after reaction and m_i is the ith component molecular mass ($i=1$ is an oxidant, $i=N$ is fuel, $i=2$ is an inert component: $\nu_i' = \nu_i''$; $i=3,\ldots, N$-1 are the reaction products). The specific heats at constant pressure for the components will be considered constant ($c_{pi} = \text{const}$). Then the mean heat capacity of the mixture c_p will depend on the concentrations of the components Y_i:

$$\hat{c}_p = \sum_{i=1}^{N} c_{pi} Y_i \tag{2}$$

Let the rectangular coordinate systems (x, y) and $(\tilde{x}, \tilde{y})$ be chosen so that the axis x would be coincident with the phase interface and would be aligned with the oxidant flow, while the axis y and $\tilde{y}$ in the gas and liquid, respectively, would be aligned against the interface. The coordinate origin coincides with the start of the boundary layer (Fig. 1).

In the derivation of equations, the effects of mass forces, thermal diffusion and diffusion pressure gradients will be neglected; the coefficients binary diffusion for different components will be considered identical ($D_{ij} = D_{kl} = D$). Then, the equations of a boundary layer in a gas, provided that the Prandtl and Schmidt numbers are equal to unity, are:

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \tag{3a}$$

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial v}{\partial y} = \frac{\partial}{\partial y} \mu \frac{\partial u}{\partial y} \tag{3b}$$

$$\rho u \frac{\partial Y_i}{\partial x} + \rho v \frac{\partial Y_i}{\partial y} = \frac{\partial}{\partial y} \mu \frac{\partial Y_i}{\partial y} + \omega_i; i = 1, \ldots, N \tag{3c}$$

$$\rho u \frac{\partial H}{\partial x} + \rho v \frac{\partial H}{\partial y} = \frac{\partial}{\partial y} \mu \frac{\partial H}{\partial y} \tag{3d}$$

$$p = \rho R T \sum_{i=1}^{N} Y_i / m_i \tag{3e}$$

where $H = \sum_{i=1}^{N} Y_i \left(c_{pi} T + h_i^0 \right) + \frac{u^2}{2}$ is the total specific enthalpy of the mixture and $h_i = c_{pi} T + h_i^o$ is the i-th component specific enthalpy.

In the case of solid fuel the equations for a boundary layer at constant heat capacity c_f, viscosity μ_f and thermal conductivity λ_f reduce to energy equation:

$$u_w \frac{\partial \tilde{T}}{\partial x} + \tilde{v}_f \frac{\partial \tilde{T}}{\partial \tilde{y}} = \frac{\lambda}{\rho c} \frac{\partial^2 \tilde{T}}{\partial \tilde{y}^2} \tag{4}$$

where $u_w = \text{const}$ is the velocity of fuel layer in the system of coordinates moving with the flame tip (in the case of steady flame over fuel layer $u_w = 0$), and $v_f = v_f(x)$ is the velocity of vertical movement of fuel, deriving from evaporation, because coordinate system in the vertical direction is moving with the phase interface.

Thus, the boundary conditions of the systems of Eqs. (3) and (4) are presented by three groups of conditions.

The conditions on the outer edge of a boundary layer in a gas ($y \to +\infty$):

$$T = T_e, p = p_e, u = u_e, Y_1 = Y_{1e}, Y_{1e} + Y_{2e} = 1$$

The conditions on the edge of a boundary layer in a fuel ($\tilde{y} \to +\infty$):

$$\tilde{T} = T_\infty, \tilde{u} = u_\infty = u_w$$

The balance relationships at the phase interface $y = 0; x > 0$ are following:

total mass flux conservation condition

$$(\rho v)_w = -(\rho \tilde{v})_{fw} \tag{5}$$

no-slip condition

$$u = \tilde{u} = u_w \tag{6}$$

condition of tangential stresses continuity

$$\tau = -\tau_{fw}, \left(\tau = -\mu \frac{\partial Y_i}{\partial y} \right) \tag{7}$$

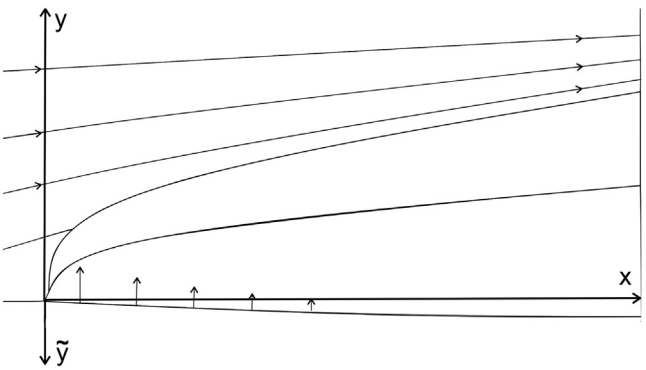

Fig. 1. Streamlines in material surface burning in the stream of an oxidant.

Download English Version:

https://daneshyari.com/en/article/8056316

Download Persian Version:

https://daneshyari.com/article/8056316

Daneshyari.com