

# Influence of Monodispersed Mist of Inert Liquid on Gas Flame Propagation

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## 1 Abstract

The combustion of premixed gas mixtures containing inert liquid microdroplets was studied using the one-dimensional approximation. The dependencies of the burning velocity and flammability limits on the initial conditions and on the properties of liquid droplets were analyzed. Effects of droplet size and concentration of added liquid were studied. For droplets evaporating in the reaction zone, the burning velocity is independent of droplet size, depending only on the concentration of the added liquid. With the increase of the droplet diameter, the droplets pass through the flame reaction zone with a further vaporization in the combustion products. It was demonstrated that for droplets above a certain size there are two stationary modes of flame propagation with a transition of hysteresis type. The transition is the result of the appearance of the super-adiabatic maximum temperature in the flame reaction zone and the temperature gradient with heat losses to the combustion products due to the vaporization of droplets as they pass through the flame reaction zone. The critical conditions are similar to the flammability limits of laminar flame with thermal mode. The maximum decrease in burning velocity and in the combustion temperature at the turning point (critical conditions) correspond to the predictions of classical theory of flammability limits.

## 2 Introduction

It is well known that inert liquids are effective fire extinguishing agents [1, 2], decreasing combustion temperature as a result of agent vaporization and the dilution of the combustible mixture. It was found that a finely dispersed water mist is more effective at decreasing burning velocity than a spray with droplets of larger size. Large inert droplets or particles can pass through the flame reaction zone with partial vaporization, which causes an increase in the amount of the agent required for flame suppression. At the same time, smaller droplets can vaporize before the flame front without significant heat losses from the

reaction zone which are required for flame extinguishment. The influence of water on flame propagation and fire suppression by water systems were studied by many researchers, for example [1-7].

The aim of this work was a detailed analytical study of laminar flame propagation in the gas mixture with monodispersed inert liquid droplets and the flammability limits in these systems including a stability analysis of such heterogeneous systems. The approach developed by Greenberg et al [8, 9] for the stability analysis of flame propagation in a rich premixed mixture of air with liquid fuel droplets was used.

### 3 Method

The mathematical model used in this paper is an extension of the model for laminar flame [10] in a combustible gas mixture with inert liquid microdroplets. The flame front surface is considered as the sheet, where the temperature derivatives and the mass concentration of the fuel or oxidizer change abruptly. It is also assumed that the flame front is at the point  $z = Z_f$ . Fresh mixture is flowing to the front from the positive  $Z$ -axis. Combustion products are flowing from the flame front sheet in the direction of negative values of the  $Z$ -axis. It is assumed that all droplets have the same diameter, which is less than the flame heat thickness. The droplets move along with the flow of the initial mixture and with the same speed. Prior to reaching the boiling point, the droplets and the gas mixture have the same temperature. Droplet vaporization occurs at a temperature above the boiling point of the liquid. It is assumed that the mass concentration of the liquid is sufficiently small that the vaporization does not significantly change the volume and composition of the mixture. Heat losses from the system are the result of liquid vaporization, and depend on the diameter of the droplets and the mass concentration of the liquid. Depending on the vaporization process and mass concentration of the liquid mixture, complete vaporization of droplets may be achieved in the flame reaction zone or in the combustion products. In this paper we investigate both cases.

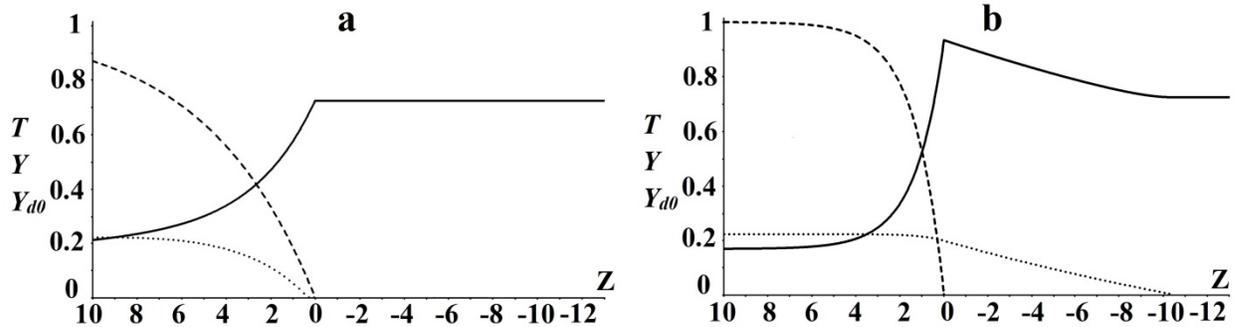


Figure 1. Typical profiles of temperature, mass concentration of the deficient component, and the mass concentration of droplets (solid, dashed and dotted lines respectively). a) The droplets vaporize completely before reaching the flame front. b) The droplets vaporize completely in the combustion products passing the flame front.

Figure 1 (a, b) shows typical temperature profiles, the mass concentration of the liquid droplets, and the mass concentration of the deficient component for the case when the droplets completely vaporized before reaching the flame front (Fig. 1a), and for the case when the droplets pass through the flame front, and complete vaporization in the combustion products (Fig. 1b). For a description of the processes we use four regions. In region 1 the temperature changes from the initial temperature to the boiling point. In region 2, the temperature of the mixture becomes higher than the boiling temperature, therefore droplets begin to vaporize, and, depending on the case under consideration, droplets either vaporize completely before reaching the flame front (Fig. 1a), or reach the flame front, without completion of vaporization

(Fig. 1b). Also, depending on the case, region 3 corresponds to the unburned mixture which doesn't contain droplets before the flame front (Fig. 1a) or the combustion products containing droplets (Fig. 1b). Region 4 corresponds to the combustion products without liquid droplets for both cases. For convenience, we denote the boiling point:  $z = Z^*$ , and the point of complete vaporization of droplets:  $z = Z^{**}$ .

For the case when the droplets vaporize completely in the flame reaction zone, the system of equations is as follows:

$$\frac{\partial^2 T_{1,3}}{\partial z^2} + V \frac{\partial T_{1,3}}{\partial z} = 0; \quad (1)$$

$$\frac{\partial^2 T_2}{\partial z^2} + V \frac{\partial T_2}{\partial z} - \Omega(T_2 - T^*) = 0; \quad (2)$$

$$\frac{1}{Le} \frac{\partial^2 Y_{1,2,3}}{\partial z^2} + V \frac{\partial Y_{1,2,3}}{\partial z} = 0; \quad (3)$$

$$V \frac{\partial Y_{2d}}{\partial z} - \frac{\Omega}{\sigma_e} (T_2 - T^*) = 0. \quad (4)$$

For the case when the droplets complete vaporization in the combustion products, the system of equations is as follows:

$$\frac{\partial^2 T_1}{\partial z^2} + V \frac{\partial T_1}{\partial z} = 0; \quad (5)$$

$$\frac{\partial^2 T_{2,3}}{\partial z^2} + V \frac{\partial T_{2,3}}{\partial z} - \Omega(T_{2,3} - T^*) = 0; \quad (6)$$

$$\frac{1}{Le} \frac{\partial^2 Y_{1,2}}{\partial z^2} + V \frac{\partial Y_{1,2}}{\partial z} = 0; \quad (7)$$

$$\frac{\partial Y_{2d,3d}}{\partial z} = V \frac{\partial Y_{2d,3d}}{\partial z} - \frac{\Omega}{\sigma_e} (T_{2,3} - T^*). \quad (8)$$

Here,  $z$  is the dimensionless spatial coordinate, scaled by the flame thickness  $l_{th} = D_{th}/U_b$ , where  $D_{th}$  is the gas thermal diffusivity and  $U_b$  is the laminar burning velocity. Mass concentration of the deficient component  $Y$  is scaled by the initial mass concentration  $Y_0 = m / (m_f + m_o)$ , where  $m$  is the mass of the deficient component in the mixture,  $m_f$  is the fuel mass and  $m_o$  is the oxidizer mass. Mass concentration of liquid in the mixture is  $Y_d = m_d / (m_f + m_o)$ , where  $m_d$  is the mass of the liquid. For convenience hereafter, the term "concentration" will be used for "mass concentration". The boiling point  $T^*$  and temperature of the mixture  $T$  are scaled by the adiabatic combustion temperature without water addition  $T_b$ . Gas velocity  $V$  is measured in units of  $U_b$ ;  $Le = D_{th}/D_{mol}$  is the Lewis number, where  $D_{mol}$  is the diffusion coefficient of the deficient component.  $\sigma_e = q_e/(c_p T_b)$  is the latent heat of vaporization, where  $q_e$  is the vaporization heat and  $c_p$  is the specific heat of the gas at constant pressure.  $\Omega = \pi N_d d_0 N_u (D_{th}/U_b)^2$  is the dimensionless heat transfer coefficient between gas and liquid droplets, where  $N_d$  is the number of droplets per volume unit,  $d_0$  is the initial diameter of droplets and  $Nu = \alpha d_0/\lambda_g$  is the Nusselt number, where  $\alpha$  is the heat transfer coefficient and  $\lambda_g$  is the gas thermal conductivity.

As the mixture flow direction is from the positive Z-axis, and the combustion products are flowing in the direction of the negative Z-axis, the boundary conditions are as follows (in both cases):

$$T_1 \rightarrow \sigma; \quad Y_1 \rightarrow 1; \quad Y_{1d} \rightarrow Y_{d0}; \quad \text{as } z \rightarrow +\infty; \quad (9)$$

$$T_4 \rightarrow \text{const}; \quad \text{as } z \rightarrow -\infty; \quad (10)$$

The boundary conditions are the same for both cases at the point where the temperature of the mixture reaches the boiling temperature of the liquid:

$$T^- = T^+ = T^*; \quad Y^- = Y^+; \quad \frac{\partial Y^-}{\partial z} = \frac{\partial Y^+}{\partial z}; \quad \frac{\partial T^-}{\partial z} = \frac{\partial T^+}{\partial z}; \quad Y_d = Y_{d0}; \quad \text{at } z = Z^* \quad (11)$$

If complete vaporization of the droplets is observed in the flame reaction zone, the boundary conditions are of the form:

$$T^- = T^+; \quad Y^- = Y^+; \quad \frac{\partial Y^-}{\partial z} = \frac{\partial Y^+}{\partial z}; \quad \frac{\partial T^-}{\partial z} = \frac{\partial T^+}{\partial z}; \quad Y_d = 0; \quad \text{at } z = Z^{**} \quad (11)$$

If the complete droplet vaporization is observed in the combustion products, the boundary conditions are as follows:

$$T^- = T^+; \quad \frac{\partial T^-}{\partial z} = 0; \quad Y_d = 0; \quad \text{at } z = Z^{**} \quad (12)$$

In the case of the complete droplet vaporization in the flame reaction zone, the boundary conditions at the flame front are as follows:

$$T^- = T_f; \quad -\frac{\partial T^-}{\partial z} = (1-\sigma)\exp\left(\frac{N}{2}\left(1-\frac{1}{T_f}\right)\right); \quad Y^- = 0; \quad \frac{1}{Le}\frac{\partial Y^-}{\partial z} = \exp\left(\frac{N}{2}\left(1-\frac{1}{T_f}\right)\right); \quad \text{at } z = Z_f \quad (13)$$

In the case of the droplet vaporization in the combustion products, the boundary conditions at the flame front are of the form:

$$T^- = T^+ = T_f; \quad \frac{\partial T^+}{\partial z} - \frac{\partial T^-}{\partial z} = (1-\sigma)\exp\left(\frac{N}{2}\left(1-\frac{1}{T_f}\right)\right); \quad Y^- = 0; \quad \frac{1}{Le}\frac{\partial Y^-}{\partial z} = \exp\left(\frac{N}{2}\left(1-\frac{1}{T_f}\right)\right); \quad \text{at } z = Z_f \quad (14)$$

The initial temperature of the mixture  $\sigma$  and the flame temperature  $T_f$  are scaled by  $T_b$ .  $N = T_a/T_b$  is the normalized activation energy of a chemical reaction, where  $T_a$  is an activation temperature.

## 4 Results and Discussion

Typical temperature and component concentration profiles, and the profile of liquid concentration are shown in Figure 1a for the solution of equations (1 – 4) with the boundary conditions (9 – 11), (12), (14). The solutions of equations (5 – 8) with the boundary conditions (9 – 11), (13), (15) are shown in Figure 1b. As already mentioned, the first case corresponds to the droplets vaporizing completely in the reaction zone, and the second one corresponds to the completion of droplet vaporization in the combustion products. Note that in the case of the completion of the droplet vaporization in the combustion products, the maximum temperature is observed in the flame reaction zone with a further temperature decrease as a result of the droplet vaporization in the combustion products.

Figure 2 shows the dependencies of the burning velocity,  $V$ , (Fig. 2a) and the flame temperature,  $T$ , (Fig. 2b) on the heat transfer coefficient,  $\Omega$ , calculated for different initial liquid concentrations,  $Y_{d0}$ . The results were obtained for the water at the following parameters:  $Le = 1,1$ ;  $\sigma_e = 1,256$ ;  $T^* = 0,222$ ;  $\sigma = 0,167$ ;  $N = 8,333$ . The shaded area corresponds to the case when the droplets pass through the flame front without complete vaporization. The remaining area corresponds to the case when the droplets vaporize completely in the flame reaction zone. The results demonstrate two modes of flame propagation depending on the heat transfer coefficient: the mode with high burning velocity and the mode with low burning velocity. The transition from one mode of flame propagation to another may be a transition of hysteresis type (Fig. 2, at concentrations higher than 0.195). The high burning velocity mode corresponds to the normal flame propagation with burning velocity decreasing with the increase of liquid concentration. Low burning velocity mode corresponds to a stationary flame with the complete vaporization of the droplets in the reaction zone. At relatively high concentrations of water, significant decreases in flame temperature and, accordingly, in the burning velocity are observed.

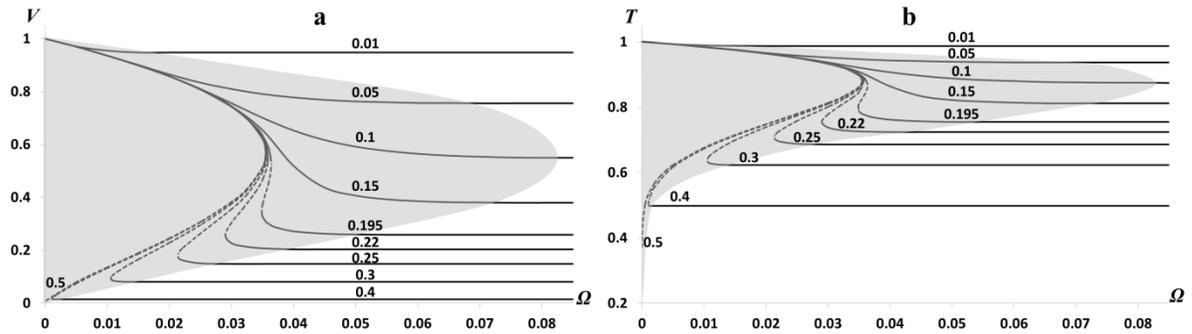


Figure 2. a) Dependence of burning velocity,  $V$ , on heat transfer coefficient,  $\Omega$ , at the different initial liquid concentrations,  $Y_{d0}$ . b) Dependence of the maximum flame temperature,  $T$ , on heat transfer coefficient,  $\Omega$ , at the different initial concentrations of liquid,  $Y_{d0}$ .

The turning point (Fig. 2a) approximately corresponds to the burning velocity in the range between 0.55 and 0.65, which is in good agreement with the results Modak et al [7]. Modak et al [7] indicated that the turning point occurs when the burning velocity is reduced approximately by 50% for simulations of methane, propane and hydrogen flames with added water droplets. Note that this result is also in a good agreement with the classical theory of flammability limits of thermal flame propagation: critical reduction in the burning velocity corresponds to the coefficient of  $1/\sqrt{e} = 0.606$  [10]. The source of the heat losses is the vaporization of droplets past the flame reaction zone causing the temperature gradient in the combustion products. Calculations show that the temperature decrease at the turning point (Fig. 2b) relative to the case without water addition corresponds approximately to one characteristic temperature interval  $RT_b^2/E$ , which is a maximum decrease in the combustion temperature in accord with the results of [10].

The stability of stationary solutions with respect to small perturbations at an exponential growth rate  $\omega$  was analyzed. Disturbed solutions were sought in the form:  $T = T^{st} + \tilde{T} \exp(\omega t)$ ;  $Y = Y^{st} + \tilde{Y} \exp(\omega t)$ ;  $Y_d = Y_d^{st} + \tilde{Y}_d \exp(\omega t)$ ;  $Z = Z^{st} + \tilde{Z} \exp(\omega t)$ , where  $\tilde{T}$ ,  $\tilde{Y}$ ,  $\tilde{Y}_d$ ,  $\tilde{Z}$  are small perturbations. The results are presented in the Figure 2, where the solid lines represent the stable solution, and dashed lines correspond to the unstable solution. Oscillatory behavior of flame propagation was not found. It can be that the oscillatory mode of flame propagation found in [11] is not related to the process of droplet vaporization.

## 5 Concluding Remarks

The dependencies of the burning velocity, the flame temperature and the flammability limits on the properties of initial gas mixture with added monodispersed water droplets were obtained. Calculations demonstrate two modes of flame propagation depending on the heat transfer coefficient: the mode with high burning velocity and the mode with low burning velocity. The jump transition of hysteresis type between modes is observed. The parameters obtained for the turning point (critical point) are in a good agreement with the findings of previous works. One dimensional stability analysis of flame propagation in the gas mixture with monodispersed water mist was performed, which doesn't demonstrate the oscillatory behavior of flame propagation for typical conditions.

## Acknowledgement

This work was supported by the Russian Foundation for Basic Research (grant #17-08-01207).

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