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GAS TEMPERATURE INFLUENCE ON SWIRLING/NON-SWIRLING FLOW CHARACTERISTICS

Ola Rashed, Badiea Hafez,

Assistant Professor, Cairo University, Faculty of Engineering, Aerospace Department, Giza Egypt

Antal Penninger

Professor, Head of the Heat Engines Department, Budapest Technical University

ABSTRACT

Liquid fuel sprays in combustion systems experience several complicated processes such as atomization, evaporation, mixing, and combustion; therefore numerous efforts have been devoted to develop the theoretical method for analyzing these processes. In this work the concern is to establish the gas temperature influence on chamber flow characteristics in the presence and absence of swirling. To achieve this goal, a separated flow model (SF) is adopted so that the vaporization is analyzed to obtain the swirling and non-swirling flow characteristics for different gas temperatures. The slip, droplet internal motion, varying gas film thickness, and changing combustion chamber temperature effects are taken into account. The effect of gas temperature on liquid Reynolds number, gas Reynolds number, droplet temperature, the regression rate, Lewis number and droplet velocity are established. The results obtained compare favorably with other mathematical model solutions and experimental data available in literature.

KEYWORDS: combustion chamber, temperature, flow characteristics, vaporization time, droplet evaporation

1. INTRODUCTION

The objective of this work is to develop a numerical solution procedure, which enables the evaluation of the gas temperature effect on combustion chamber flow characteristics in the absence and presence of swirling.

Studies regarding gas/droplet multiphase flows can be classified according to their point of focus: single droplet, multiple droplets, or sprays. Comprehensive reviews of the relevant fundamental transport mechanisms are given in ref [1-3]. Generally the spray models are divided into two major categories, the locally homogeneous flows (LHF), and the separated flow models (SF). In the simple LHF models, ref [4] the different phases are assumed to have identical properties at each point in the flow, which is only valid for flows with extremely small droplets. The SF approach adapted in this work considers the complex inter-phase transport phenomena, the multiple droplet size, and the variable coupled phase properties, as well as the quasi-steadiness of the boundary layer surrounding the droplet ref [5-10]. The problem modeled in this work is of single-component fuel

injected by an airblast atomizer with droplets subjected to interfacial surface tension and exposed to forced convective gas flow. It is assumed that near the exit of the atomizer, the flow is in the form of ligaments surrounded by hot gases. After an increment of time these ligaments reach a certain distance, where they start to break up and form droplets possessing internal circulation. Knowing the fuel properties, air properties and the atomizer dimensions this distance is determined from the graphs developed by Lefevbre ref [11]. These droplets move in the hot gas stream, and accelerate with time. The gas adjusts to their presence by forming a boundary layer around each one, internal circulation starts in the droplet. Exposed to drag, shear forces, and to uneven heating to its surface as well as being surrounded by thermal and mass boundary layers, the droplet evaporates with decreasing relative velocity while moving along the combustion chamber. These processes influence the state of the gas; i.e. the gas stream is retarded, cooled and enriched with fuel vapors. The changes in the gas phase properties in turn influence the dynamics and vaporization of the

droplets, which are subsequently injected. All these gas-phase and liquid phase processes are modeled by a system of unsteady equations, namely the mass, momentum, and energy equations as well as the equation of state. This model includes the effects of variable thermo-physical properties, gas film non-unitary Lewis, the Stefan flow, internal circulation and transient liquid heating.

Due to the presence of the relative motion between the gases and the droplets, the existing shear stress and the heat and mass flux at the interface, the liquid-phase and gas phase equations are non-linear and coupled. They require an iterative procedure to solve them simultaneously.

2. GOVERNING EQUATIONS

2.1 Gas-Phase Equations

The gas phase governing equations describing the model can be written generally as following

$$\frac{\partial \rho_g}{\partial t} + \nabla(\rho_g v_g) = S_m \quad (1)$$

$$\frac{\partial(\rho_g v_g)}{\partial t} + \nabla(\rho_g v_g v_g) = \nabla(\rho_g v_g \nabla v_g) - \nabla(p) + S_M \quad (2)$$

$$\frac{\partial(\rho_g h_g)}{\partial t} + \nabla(\rho_g v_g h_g) = \nabla(k_g \nabla T_g) + S_e \quad (3)$$

$$\frac{\partial(\rho_g Y_v)}{\partial t} + \nabla(v_g \rho_g Y_v) = \nabla(\rho_g D_c \nabla Y_v) + S_m \quad (4)$$

where p , ρ , v , T , and t are the pressure, density, velocity, temperature and time respectively. The quantities S_m , S_M , and S_e represent the mass, momentum, and energy exchange terms, respectively.

The vapor-mass fraction Y_v is defined as: $Y_v = \frac{\rho_v}{\rho_g}$

The ideal-gas equation of state is also adopted.

$$P = \rho_g ((R_a + Y_v(R_v - R_a))T_g) \quad (5)$$

The gas-phase governing equations are solved to obtain the gas flow characteristics, by using a 2nd order Runge-Kutta technique for the equation of motion and a numerical explicit finite difference scheme for the species and momentum equations. The liquid-phase solution is used as input to this scheme and then iteration is performed to insure the correctness of the obtained results.

The swirling flow was solved by introducing the swirling effect as a factor to the temperature profile according to the experimental data obtained by Schmidt et al. ref (12), McDannel et al. ref (13), Chen et al. ref (14) and Tran et al. ref (15). The obtained center line temperature is as follows:

$$\text{Low swirl} \quad T = 271.6 * x^{0.355}$$

$$\text{Medium swirl} \quad T = 521.01 * x^{0.238}$$

$$\text{High swirl} \quad T = 1070.03 * x^{0.0792}$$

2.2- Liquid - Phase Equations

2.2.1 Droplet Motion Equations

For the x-direction droplets, labeled by a subscript k are assumed to obey the following equations:

$$\frac{dx}{dt} = V_k \quad (6)$$

$$\frac{dV_k}{dt} = \rho_r L_r^2 t_r \left(\frac{3 C_D \mu Re_k (V - V_k)}{16 r_k^2} \right) \quad (7)$$

$$\frac{dr_k^2}{dt} = -2 \rho_r L_r^2 t_r M_k \quad (8)$$

M_k , ρ_r , L_r , t_r , Re_k , C_D are the non-dimensional vaporization rate, the gas density ratio, the gas-phase length scale, and the convective to diffusive time scale ratio, the particle Reynolds number and the drag coefficient respectively, and are defined in ref (16).

In order to obtain the velocity of the droplets, the distance traveled, the droplet radii, these governing equations are solved using a 2nd order Runge- Kutta Scheme. The obtained results are then used as input for the gas phase problem, and the iterative procedure is performed until convergence is reached.

2.2.2 Droplet Mass & Heat Transfer

As described by Feath ref (17), the droplet heat-up and evaporation calculations use the following correlations to obtain the mass & heat transfer rates

$$\frac{\dot{m}_k d}{\rho D_f} = 2 N_s \ln(1 + B_M) \quad (9)$$

$$\frac{hd}{k} = 2 N_p \frac{\ln(1 + B_M)^{Le-1}}{((1 + B_M)^{Le-1} - 1)} \quad (10)$$

where h , d , D_f , k , and \dot{m}_k are the heat transfer coefficient, the droplet diameter, the fuel-mass diffusivity, thermal conductivity and mass evaporation rate per unit area. For effective computational time and accuracy, an “ effective value of the liquid thermal conductivity k “ is used to calculate and to account for the droplet internal circulation.

The N_s and N_p are functions of Reynolds, Prandtl, Schmidt and Lewis numbers defined in Ref (17).

The mass and the thermal boundary layer thickness are evaluated by taking the effect of the Stefan flow on the heat and mass transfer.

2.2.3 Droplet Internal Temperature

The temperature distribution within the droplet is obtained by solving the energy equation subject to the convective boundary conditions at the droplet surface by a Crank- Niclson scheme.

$$\frac{\partial T_1}{\partial t_b} = \frac{\partial^2 T_1}{\partial \tilde{r}^2} + \left(\frac{2}{\tilde{r}} - \tilde{r} M_k K \right) \frac{\partial T_1}{\partial \tilde{r}} \quad (13)$$

Where the droplet characteristic radius \tilde{r} , the time t_b , and liquid temperature T_l are defined as

$$\tilde{r} = \frac{r}{r_{kinitial}}, \quad t_b = \alpha \int_0^t \frac{dt}{r_k^2}, \quad \text{and} \quad T_l = \frac{T_l - T_o}{T_b - T_o}$$

T_b is the boiling temperature, K is defined as follows:

$$K = \frac{\rho_c D_c}{\alpha_l \rho_k}$$

and α is the diffusivity. The average physical properties (T , C_p , μ , K , D , ρ) are calculated by the 1/3 rule ref (18)

$$\Phi = \Phi_s + 1/3 (\Phi_g - \Phi_s)$$

3. RESULTS

The gas temperatures influences the amount of heat transfer and directly affects the gas density, velocity, viscosity, the specific heat, and the thermal conductivity. These parameters in turn affect the amount and rate of heat transfer from the gases to the surface and the core of the droplet. Increasing the gas temperature decreases the heating- up period of the droplet, which leads to a reduction in its evaporating time. This increase in the gas temperature though favorable, is limited by the engine material and also by the stability of the combustion process itself.

The rate of vaporization is enhanced by the increase of temperature. At low gas temperatures heating up consumes more time than at higher temperatures. Consequently the transient mass diffusion is slower at these lower temperatures. The dimensionless diffusion coefficient D displayed against time in Fig. (1), increases with temperature. The dimensionless thermal conductivity (K/K_o) shown in Fig.(2) increases with time and temperature, indicating that the vaporization process accelerates towards the end of the evaporation period. As seen from the Fig (3) the radii decreases with time. Increasing the gas temperature, which in turn increases the thermal conductivity, the diffusivity and the surface regression, leads to a decrease in

evaporation time. From fig (4), it is noted that the droplet velocity increases with the progress of time. By increasing the temperature, the droplet velocity kept the same trend but decreased slightly in value. This is because at higher temperatures, there is higher heat and mass transfers, which lead to rapid decreases in evaporating time. The higher surface regression causes also changes in specific heat, thermal conductivity, and droplet velocity. Fig (5) shows the Lewis number versus time at different gas temperatures. At higher gas temperatures, the Lewis number decreases rapidly, because it is inversely proportional to the gas film fuel concentration, which grows quickly at higher temperatures. Initially for the cold droplet surface the vapor concentration in the film is low, thus the Lewis number is very high. Fig (6) displays the liquid Reynolds number against time. It is clear that the liquid Reynolds number increases, then decreases quickly. The initial Reynolds number increases due to the increase in droplet velocity, which is accompanied by a negligible change in its diameter. By the end of the heat-up period, the surface regression starts so the decay of the Reynolds number develops quickly. Due to the changes in droplet velocity, density, viscosity and the higher rate of vaporization accompanied by the higher temperatures the Reynolds number increases and starts to decrease in a shorter time than at lower temperatures. Fig (7) displays gas Reynolds number versus time at different gas temperatures, it shows that the gas Reynolds number decreases throughout the droplet lifetime. The higher reduction rate is at the higher temperatures. The different initial values of Reynolds number are due to the changes in gas density and viscosity. Fig (8) shows the droplet surface temperature versus time at different gas temperatures. It is clear that at high gas temperatures the droplet surface temperature increases in a more rapid manner than at low temperatures which means that the heat- up period of the droplet decreases, thereby causing a reduction in the droplet evaporating time. At low gas temperatures the transient mass diffusion in liquid is important for maintaining a stable combustion process, so that it is not possible to reduce the gas temperature without changing other parameters such as fuel type, fuel air ratio, type of atomizer. Also exceeding a certain high temperature range leads to instant evaporation causing combustible instabilities.

As seen from the results displayed in Fig (9)- Fig(12) the presence of swirling is favorable as it reduces the evaporation time, increases the droplet velocity, the liquid Reynolds number, and the droplet surface temperature reaches its boiling temperature faster. The model was validated against other models developed recently by researchers working in this field ref. [19,20]. The comparisons with Sirignano 1983 and Chiang and Chiang 1996, and is good agreement with those models as well as the recent models and experimental data [8,10].

4. CONCLUSION

The developed program has proven to be effective and efficient mean in determining the effect of temperature on the chamber flow. The swirling effect is accounted for, which will help the designer in the estimate of combustion chamber characteristics.

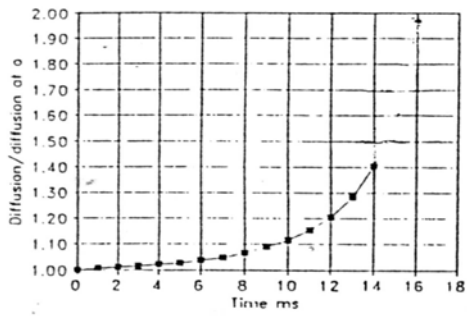


Fig.1. Diffusion versus Time

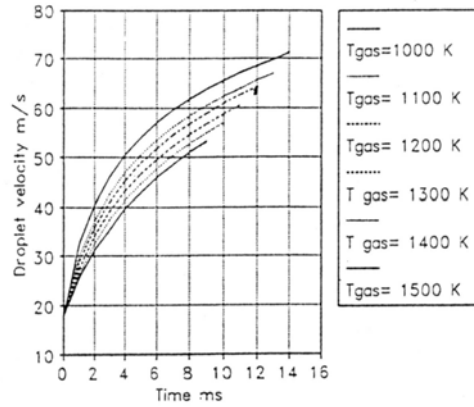


Fig.4. Drop Velocity vs. Time

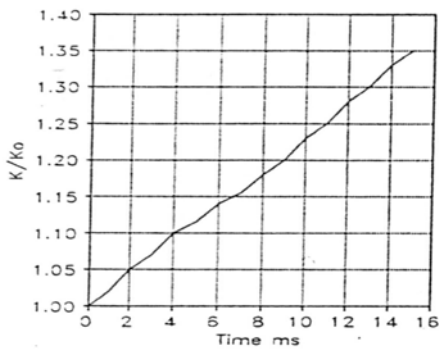


Fig.2. Thermal Conductivity vs. Time

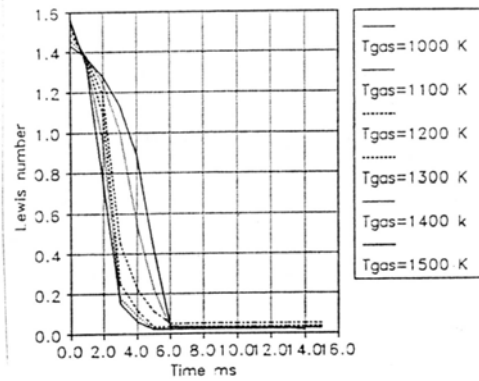


Fig.5. Lewis Number vs. Time

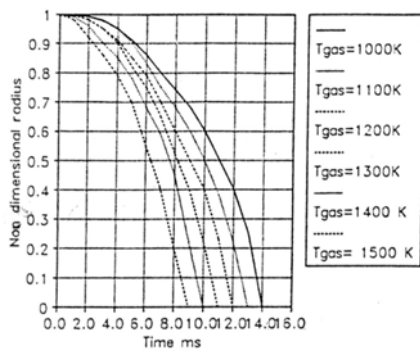


Fig.3. Droplet Radius vs. Time

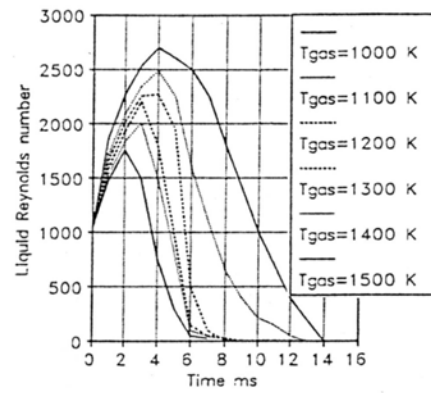


Fig.6. Re_{liquid} vs. Time

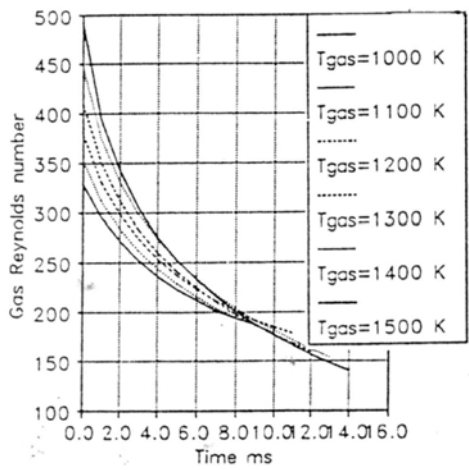


Fig.7. Re_{gas} vs. Time

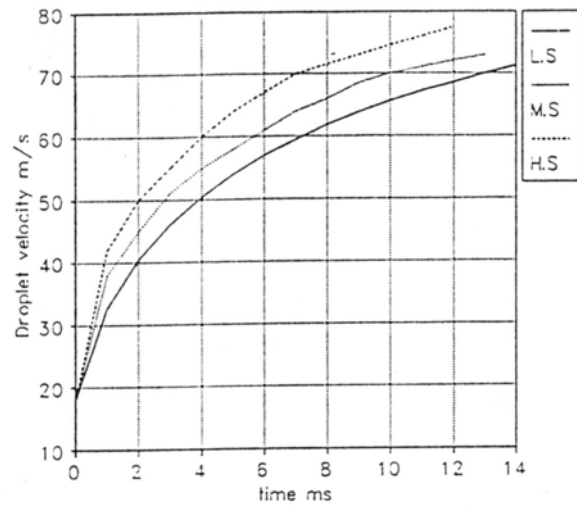


Fig.10. Swirl Effect on Drop Velocity

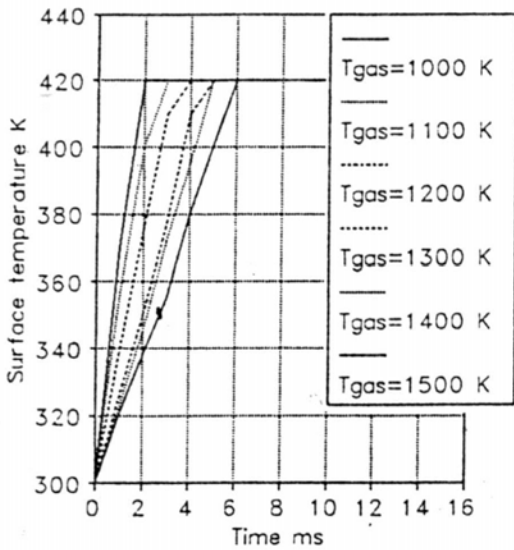


Fig.8. Drop Surface Temp. vs Time

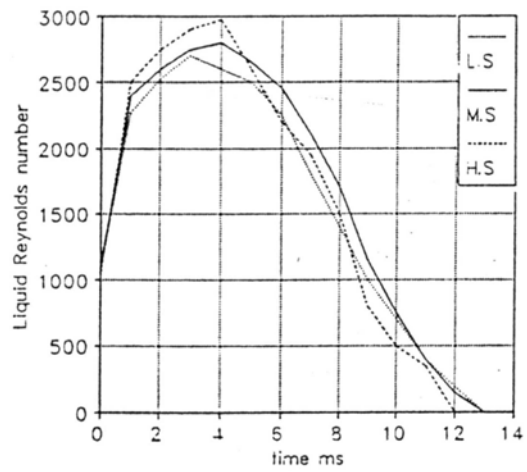


Fig.11. Swirl Effect on Re_{liquid}

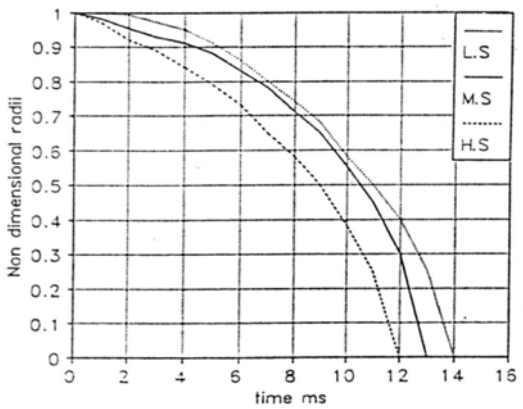


Fig.9. Swirl Effect on Evap. Time

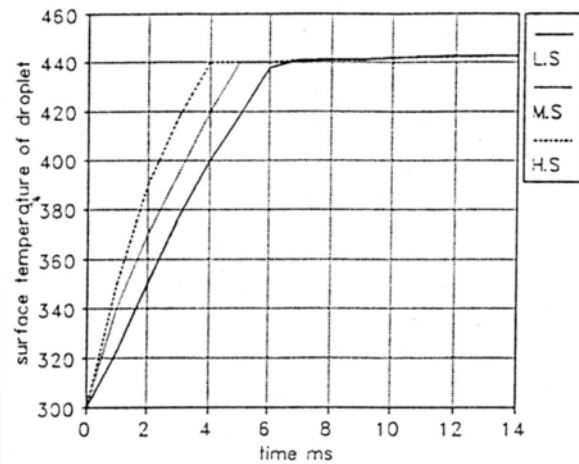


Fig.12. Swirl Effect on Surface Temp.

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