Numerical Study of the Effects of Nanoparticles on Fuel Diffusion Combustion

M. A. Waheed

Department of Mechanical Engineering, College of Engineering Federal University of Agriculture, P.M.B 2240, Abeokuta, Ogun State, Nigeria
E-mail: waheedma@funaab.edu.ng

Abstract. The work investigates diffusion combustion of nanofuel made from the mixture of the base fuel and Al₂O₃ nanoparticles in a two-dimensional combustor with stationary horizontal walls. The numerical study was carried out by solving the problem governing equations including the continuity, momentum, energy and species concentration equations formulated for two-dimensional unsteady-state laminar convection using the finite volume method. The fully implicit scheme was used for the discretization in time; while upwind differencing and central differencing were used to discretize the convective and diffusive terms respectively. The results show that the values of the temperature and fuel concentration throughout the domain were higher during combustion of nanofuel than that of the base fuel only. Specifically, for flow streams at Re = 100, the addition of nanoparticles of volume fraction, φ = 0.05, enhanced the outlet average temperature of the combustor by 13% over that of ordinary fuel. Also, the wall temperature at steady state for nanofuel combustion is 7.4742 compared with 6.5897 for the base fuel. The high concentration of nanofuel is an indication of incomplete combustion which implies that more heat and higher temperature can be generated by increasing the flow stream of air.

Keywords: Combustion, diffusion, nanofuel, numerical modelling

1. Introduction

There is renewed interest in the development of alternative fuels due to the depletion of fossil fuels, increasing fuels prices, environmental considerations and the need to improve the efficiencies of energy systems [1]. Nanofuels were conceived as a class of nanofluids which serve as alternatives to conventional fuels. They are made by adding metallic nanoparticles additives to base fuel resulting in fuels with higher calorific value, high energy density with high reactive interfacial area which allows increased fuel-oxidiser reaction to produce potential output and thus help in the reduction of soot formation, shortened ignition delay and combustion time [2 – 4]. The high heat of formation of nanofuel is released rapidly thereby saving on specific fuel consumption and significant reduction in green-house gases [5]. Sonawane et al. [6] performed experiments to investigate the thermo-physical properties and the heat transfer rate of Al₂O₃/aviation turbine nanofluids. The thermal conductivity, dynamic viscosity and heat transfer rate were enhanced due to the addition of nanoparticles. Tyagi et al. [7] studied the ignition properties of diesel fuel by varying the size and quantity of Al and Al₂O₃ nanoparticles in a diesel fuel. Increased ignition probability and shortened ignition delay were observed. Sajeewan and Sajith [8] conducted an experiment to investigate the catalytic activity of nanoparticles in an IC engine combustion. It was observed that fuel properties such as viscosity, flash and fire point increase with the addition of nanoparticles. A 30% in NOₓ reduction was observed.

The diffusion combustion of Al₂O₃-based nanofuel in a square combustor is studied in this work by solving the problem governing equations numerically. The diffusion combustion of fuel involves convection, diffusion and reaction with respect to the characteristic time scales in which the fuel and oxidizer are not mixed before they enter the combustion chamber and are separated by a thin boundary layer [9 - 10]. Mixing between the two substances occurs at intermolecular level. The entropy of the molecular interactions and mixing increases with the ambient temperature of the chamber, leading to
the rise in internal energy. This continues to rise until the activation energy for chemical reaction is reached. Fuel combustion is exothermic in which the unlocked energy content of fuel is released. There are a couple of parameters that indicate the progress of combustion. These include the temperature, fuel and oxygen concentration distribution within the flow domain, the inlet velocity of the fuel and air streams, ambient temperature, inlet temperature, heat of formation and boundary conditions of the combustor. High energy is released when the temperature within the flow domain is high. This indicates near or completes combustion and high combustion efficiency. The presence of high fuel concentration however means combustion is not progressing as it should, and combustion efficiency is low. When this happens, soot formation occurs. This work therefore studies the concentration and temperature fields in the diffusion combustion of fuel and nanofuel made from the mixture of the base fuel and Al₂O₃ nanoparticles of 0.05 volume fraction in a two-dimensional combustor with stationary horizontal walls. The fields will show insight into the combustion process of the fuels.

2. Problem Description and Theoretical Model

The schematic representation of the physical configuration of the problem is presented in Figure 1.

\[ \frac{\partial C_f}{\partial t} + u \frac{\partial C_f}{\partial x} + v \frac{\partial C_f}{\partial y} = \frac{1}{\rho_e f} \left( \frac{\partial^2 C_f}{\partial x^2} + \frac{\partial^2 C_f}{\partial y^2} \right) + C_f^+ \]  

(1)

Oxygen concentration transport equation:

\[ \frac{\partial C_a}{\partial t} + u \frac{\partial C_a}{\partial x} + v \frac{\partial C_a}{\partial y} = \frac{1}{\rho_e a} \left( \frac{\partial^2 C_a}{\partial x^2} + \frac{\partial^2 C_a}{\partial y^2} \right) + C_a^+ \]  

(2)

Energy transport equation:
\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{1}{Pe} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + T^+ \tag{3}
\]

Kinematics equation:

\[
\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = \omega \tag{4}
\]

Vorticity transport equation:

\[
\frac{\partial \omega}{\partial t} + u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} = \frac{1}{Re} \left( \frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) \tag{5}
\]

The variables \( C_f \) and \( C_a \) represent the concentration of air and oxygen respectively while \( T \) represents temperature. The equations for fluid flow are given by the vorticity-stream function formulation for continuity equation in Eq. (4) and momentum equation in Eq. (5). The reacted fuel and oxygen are denoted by the source terms, \( C_f^+ \) and \( C_a^+ \). The relationship between the two parameters are given in Eq. (6)

\[
C_f^+ = C_a^+ = - \frac{L}{U} k C_f C_a \tag{6}
\]

where \( k \) is the reaction rate constant. The expression for \( k \) is given in Eq. (7)

\[
k = k_0 e^{-E/RT} \tag{7}
\]

where \( E \) is the activation energy, \( R \) is the gas constant and \( T \) is the temperature. The product \( RT \) is the kinetic energy of the reaction.

If we make \( L \) and \( U \) the reference scales for length and velocity respectively, we can write \( k_0 L/U = K \) and \( E/RT = T_E \). Based on these relations, Eq. (6) can be expressed as

\[
C_f^+ = C_a^+ = -k \frac{C_f C_a e^{-T_E/T}} \tag{8}
\]

The heat source, \( T^+ \) in Eq. (3) is the generation of heat due to the combustion reaction. It can be expressed as

\[
T^+ = -H_t C_f C_a e^{-T_E/T} \tag{9}
\]

where \( H_t \) is the rate of heat generation.

**Reference Scales**

Following Kotake and Hijikata [11] the non-dimensional variables used to normalize the problem governing equations are:

1. Length: The width of flow inlet is \( L \). It is constant all through the flow passage.
2. Velocity: The average velocity of flow at inlet is \( U \). The inlet velocity for fuel and oxygen is denoted by \( U_f \) and \( U_a \) respectively. The width of the oxygen port can be expressed as \( y_0 = Y_0/L \). Hence, the relationship between \( U, U_f \) and \( U_a \) is

\[
U = y_0 U_{a0} + (1 - y_0) U_{f0} \tag{10}
\]

3. Concentration: The concentration of fuel and oxygen at inlet is denoted by \( C_{f0} \) and \( C_{a0} \) respectively.
4. Temperature: The temperature of fuel and oxygen at inlet is denoted by \( T_f \) and \( T_a \) respectively.

**Nondimensional Parameters**

The nondimensional variables which occur in the problem include the Reynolds number, which is expressed as

\[
Re = UL/v \tag{11}
\]

The Peclet number of the flow is given as

\[
Pe = Re Pr = \frac{C_p \mu}{k} \tag{12}
\]

For fuel: \( Pe = \frac{C_{pf} \mu_f}{k_f} \)

For oxygen: \( Pe = \frac{C_{pa} \mu_a}{k_a} \)

The concentration ratio at inlet can be expressed as

\[
R_{fa} = \frac{C_f}{C_{a0}} \tag{13}
\]

The velocity ratio can be expressed as

\[
R_{fa} = \frac{C_f}{C_{a0}} \tag{13}
\]
\[ U_{fa} = \frac{U_f}{U_{a0}} \]  

**Boundary Conditions**

The domain boundaries can be divided into five sections following Kotake and Hijaikata [11]. The boundary conditions for these sections are given in Eqs. (15) – (19).

**Inlet (oxygen stream):**

\[
\begin{align*}
C_a &= C_{a0} \\
C_f &= 0 \\
u &= u_a(y) = 6U^o_{a0}(y_o - y^o); U^o_{a0} \equiv \frac{1}{y_o+(1-y_o)U_{fa}}; y^o \equiv \frac{y_o-y}{y_o} \\
T &= T_a \\
\psi &= y_0U^o_{a0}[1 - (3y^{o2} - 2y^{o3})] \\
\omega &= \frac{6U^o_{a0}}{y_o}(1 - 2y^o)
\end{align*}
\]  

**Inlet (fuel stream):**

\[
\begin{align*}
C_f &= C_{f0} \\
C_a &= 0 \\
u &= u_f(y) = 6U^o_{f0}(y_o - y^{o2}); U^o_{f0} \equiv \frac{1}{y_o+(1-y_o)U_{fa}}U_{fa}; y^o \equiv \frac{y_o-y}{(1-y_o)} \\
T &= T_f \\
\psi &= (1 - y_0)U^o_{f0}(3y^{o2} - 2y^{o3}) + y_0U^o_{a0} \\
\omega &= \frac{6U^o_{f0}}{(1-y_o)}(1 - 2y^o)
\end{align*}
\]  

**Outlet:**

\[
\frac{\partial c_f}{\partial x} = 0; \frac{\partial c_a}{\partial x} = 0; \frac{\partial u}{\partial x} = 0; \frac{\partial T}{\partial x} = 0; \frac{\partial \psi}{\partial x} = 0; \frac{\partial \omega}{\partial x} = 0 \]  

\[ x = 1; \quad 0 < y < 1 \]

**Top wall:**

- Stationary wall

\[
\frac{\partial c_f}{\partial y} = 0; \quad C_a = 0; \quad u = 0; \quad v = 0; \quad \frac{\partial T}{\partial y} = 0; \quad \psi = 1; \quad \omega = \frac{\partial^2 \psi}{\partial y^2}  
\]  

\[ 0 < x < 1; \quad y = 1 \]

**Bottom wall:**

- Stationary wall

\[
C_f = 0; \quad \frac{\partial c_a}{\partial y} = 0; \quad u = 0; \quad v = 0; \quad \frac{\partial T}{\partial y} = 0; \quad \psi = 0; \quad \omega = \frac{\partial^2 \psi}{\partial y^2} 
\]  

\[ 0 < x < 1; \quad y = 0 \]

**Nanofuel Properties**

For nanofluids in general, the thermophysical properties can be estimated using empirical expressions in the absence of experiments. The most important properties are viscosity, thermal conductivity, specific heat and density. It is assumed that the nanofluid (in this case, fuel with nanoparticles) is homogenous in nature. The nanoparticles are evenly dispersed and free of coagulants. The properties are constant all through the fluid volume and the effect of radiation is negligible.

**Viscosity**

Brinkman [12] presented an empirical model for estimating the dynamic viscosity of a nanofluid. The model is presented in Eq. (20).

\[
\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^2.5} 
\]

**Thermal conductivity**

The thermal conductivity of a nanofluid mixture can be estimated with the model of Mintsa et al. [13].
\[ k_{nf} = k_{bf} + 3 \Phi \left( \frac{k_p - k_{bf}}{2k_{bf} + k_p - \Phi (k_p - k_{bf})} \right) k_{bf} \]  

\[ \text{Specific heat} \]

A commonly used nanofluid model for estimating specific heat capacity is that of Zhou and Ni (2008).

\[ C_{p_{nf}} = \Phi C_p + (1 - \Phi) C_{bf} \]  

**Density**

The density of nanofluid was approximate using the empirical expression of Pak and Cho (1998) in Eq. (23).

\[ \rho_{nf} = \Phi \rho_p + (1 - \Phi) \rho_{bf} \]  

In Eqs. (20) to (23), the subscripts \( nf \) and \( bf \) represent nanofluid and basefluid respectively while \( \Phi \) represents the volume fraction of nanoparticles in the nanofluid.

**Effect on Activation Energy**

Activation energy is the least amount of energy required to start combustion. The activation energy can be determined from reaction rate at constants different temperatures based on the Arrhenius equation [14].

\[ \ln \left( \frac{H_{nf}}{H_{bf}} \right) = \frac{E_a}{R} \left( \frac{1}{T_f} - \frac{1}{T_{nf}} \right) \]  

Where the subscripts \( f \) and \( nf \) denote fuel and nanofuel respectively. The variables \( H \), \( E_a \), \( R \) and \( T \) respectively represent reaction rate, activation energy, gas constant and reference temperature.

3. **Numerical Solution**

The finite volume method (FVM), which is a suitable and capable numerical technique for solving various types of simulation problems involving conservation laws [15], was used to solve the species concentration, temperature and flow equations.

The domain is divided into control volumes over each of which the conservation equation is integrated. A linear algebraic set of equations is obtained and solved to get the parameter distribution over the domain. For any generic conservation equation with diffusive and convective terms, the equation can be represented as

\[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = \left( \frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2} \right) + f(x, y) \]  

The convective terms are discretized using Upwinding Differencing Scheme (UDS) while the diffusive terms are discretized using Central Differencing Scheme (CDS). For the discretization in time, the fully implicit scheme is used. The fully implicit scheme is unconditionally stable, so we can employ any time step size [16].

Eq. (25) becomes:

\[ (\alpha \Gamma)_{i,j} - (\alpha \Gamma)_{i,j}^0 = F_w \Gamma_{i-1,j} - F_{i-1,j} + F_i \Gamma_{i,j-1} - F_{i,j-1} + D_{e} \left( \Gamma_{i+1,j} - \Gamma_{i,j} \right) - D_{w} \left( \Gamma_{i,j} - \Gamma_{i-1,j} \right) + D_{n} \left( \Gamma_{i,j+1} - \Gamma_{i,j} \right) - D_{s} \left( \Gamma_{i,j} - \Gamma_{i,j-1} \right) + S \Delta x \Delta y \]  

where \( \alpha = \Delta x \Delta y / \Delta t \); \( F_w = u_{i-1,j} \); \( F_i = u_{i+1,j} \); \( F_n = u_{i,j+1} \); \( F_s = u_{i,j-1} \); \( S = f(x, y) \)

also, \( D_e = D_w = 1 / \Delta x \) and \( D_n = D_s = 1 / \Delta y \)

\( \Delta x, \Delta y \) and \( \Delta t \) are the spatial step in x-direction, spatial step in y-direction and time step respectively.

By substituting for the appropriate boundary conditions, the link equation in Eq. (27) is arrived at.

\[ A_{i,j} = A_{i-1,j} + A_{i+1,j} + A_{i,j+1} + A_{i,j-1} + A_{i,j}^0 + (F_w - F_{i-1,j}) + (F_{i,j} - F_{i,j+1}) - S_{i,j} \]  

where \( A_{i-1,j} = F_w + D_{w}; A_{i+1,j} = D_{e}; A_{i,j+1} = D_{n}; A_{i,j-1} = F_s + D_{s}; A_{i,j}^0 = \alpha; \)

\( S_{i,j} = -S_u / \Gamma_{i,j} \)

For each control volume, the algebraic equation in Eq. (27) is solved

\[ \Gamma_{i,j} = \frac{A_{i-1,j}F_{i-1,j} + A_{i+1,j}F_{i+1,j} + A_{i,j+1}F_{i,j+1} + A_{i,j-1}F_{i,j-1} + A_{i,j}^0 F_{i,j} + S_u}{A_{i,j}} \]  

4. **Results**

The results of the numerical experiments are presented in the forms of the temperature distribution, fuel and oxygen concentrations within the flow passage and the domain boundaries, together with the combustion products concentration profiles at the outlet.
Starting with the thermo-physical properties of the nanofuel, the volume fraction of nanoparticles added to the fuel, $\phi = 0.05$. The sample nanoparticles chosen for this study is $\text{Al}_2\text{O}_3$. A generic fuel is chosen with all properties with the value of unity. The properties of both these fuel and nanoparticles are presented in Table 1.

| Properties | Fuel | $\text{Al}_2\text{O}_3$ | Nanofuel | Oxygen |
|------------|------|----------------|----------|--------|
| Density (kg/m$^3$) | 1 | 3950 | 198.45 | 1.33 |
| Thermal Conductivity (W/K) | 1 | 18 | 1.13 | 0.0337 |
| Specific heat (W/kg K) | 1 | 880 | 44.95 | 0.91 |
| Viscosity (kg/m$^2$) | 1 | 1.14 | 0.000029 |

The estimated properties of the nanofuel are also presented. The density of the fuel increased by about 198%, and the thermal conductivity was enhanced by 13%. There are also increase in values of specific heat capacity and viscosity. The large percentage in the values of the properties can be explained by large differences in the property values of both fuel and nanoparticles.

The inlet temperature profile at inlet is shown in Figure 2. The lower section shows the profile for oxygen stream while the upper section profile is for the fuel stream. The concentration profiles for fuel and oxygen are also shown in Figure 3a and Figure 3b.

![Figure 2: Inlet temperature profile up to 5secs with $\Delta t = 0.2$](image)

The parameter values are:

- Fuel: $T_E = 4$; $H_t = 10$; $U_{f_0} = 1$; $U_{a_0} = 1$; $T_f = 1$; $T_a = 1$; $T_0 = 2$; $nx = ny = 20$
- Nanofuel: $T_E = 3.53$; $H_t = 10$; $U_{f_0} = 1$; $U_{a_0} = 1$; $T_f = 1$; $T_a = 1$; $T_0 = 2$; $nx = ny = 20$
Figure 3a: Fuel concentration profile at inlet

Figure 3b: Oxygen concentration profile at inlet

The profiles show that the variables $T$, $C_f$ and $C_o$ are functions of $y$ along the inlet width. Fuel and oxygen flow along positive $x$-direction and diffuse into one another before combustion takes place. Combustion started when the temperature of the mixture is high enough that the heat generated is greater or equal to the activation energy. At the outlet of the domain, which is far upstream, combustion reaction is complete, and the amount of oxygen present is almost non-existent. With the addition of nanoparticles, the activation energy is reduced by approximately 11%. The nanoparticles serve as catalysts by increasing the reaction rate, increasing thermal capacity and thermal conductivity. Figure 4a and 4b shows the concentration profiles of the products at the outlet of the domain for a stationary wall. It can be clearly seen that the steady state concentration for nanofuel products is higher than that of fuel products after combustion. This can be attributed to higher heat generation during combustion which results in a more complete combustion and higher amount of product generation from nanofuel.

Figure 4a: Fuel concentration profiles at outlet, $\Delta t = 0.2$

Figure 4b: Nanofuel concentration profiles at outlet, $\Delta t = 0.2$

The distribution of fuel concentration is shown in Figure 5a and while that of nanofuel is shown in Figure 5b at $t = 5$ secs. The concentration of nanofuel is higher in any part of the domain than the corresponding concentration of fuel. Nanofuel achieved better distribution and circulation within the domain. While we can conclude on better fuel efficiency, the chance of incomplete combustion is however higher in the presence of higher nanofuel distribution because oxygen is rapidly consumed within the domain.
Figure 5a: Fuel concentration within the domain at \( t = 5 \) secs

Figure 5b: Nanofuel concentration within the domain at \( t = 5 \) secs

Figure 6 shows the oxygen distribution with the domain for stationary wall combustion. The difference in the distribution of oxygen for fuel and nanofuel combustion cases is negligible. Oxygen is immediately consumed as it enters the domain at about 20% of the length of the passage. The same observation is made for both fuel and nanofuel. Reducing the fuel-oxygen concentration ratio by increasing the oxygen concentration by a large value had little effect on the distribution.

Figure 6: Oxygen distribution within the domain

The rate of heat generation is because of lower activation energy and faster release of the locked energy content of the fuel. A higher temperature distribution highlights better fuel efficiency which can lead to improved system performance. At the start of combustion, temperature increases rapidly with time and approached an asymptotic steady state value. Figure 7 presents the variation in the average temperature values with time for fuel and nanofuel combustion at the outlet of the domain. At \( t = 5 \) secs, the outlet temperature is at a steady state value. The value for nanofuel is about 13% higher than that of fuel combustion. This is a clear indication of the higher release of energy in nanofuel combustion. The metallic particles contained within the bulk fuel has very high specific heat capacity and their energy density is high as well. It is expected that the temperature along the walls follow the same trend.
In Figure 8, the upper wall temperature is presented for fuel and nanofuel combustion at different time levels with $\Delta t = 2$. With increasing time step, the difference between the inlet end (at $x = 0$) and the outlet end (at $x = 1$) keeps increasing until an asymptotic value is attained. The maximum temperature for nanofuel combustion is 7.4742, while that of fuel combustion is 6.5897. This is another affirmation of greater heat release in nanofuel.

![Figure 7: The temperature profile of the domain](image)

![Figure 8: Temperature profile along the upper wall for fuel combustion (left) and nanofuel combustion (right)](image)

Figure 9 shows the temperature distribution within the combustion chamber for different time frames for stationary wall boundary condition. At $t = 1$ sec, the distribution within the chamber looks chaotic. Combustion is just starting because the temperature at inlet is higher than the outlet and inner temperatures.

| Fuel       | Nanofuel  |
|------------|-----------|
| $t = 1$ sec| $t = 1$ sec|
The temperatures at any cross section are also largely uneven. As combustion reaction commences, the temperature distribution pattern changes at $t = 3$ secs onwards. The temperature rises as we move along the length of the domain from left to right. The increase in temperature gets more obvious with increase in time step. Generally, a higher temperature is observed in Nanofuel combustion.

5. Conclusion

The simulation of fuel and nanofuel combustion in a diffusion flame setup was performed, examined and compared. Adding nanoparticles to fuel increases the thermal conductivity, heat capacity and viscosity of the nanofuel mixture and causes a reduction in the activation energy. The nanoparticles
volume fraction used is 0.05. Temperature is observed to increase rapidly as combustion commences and slows gradually until a steady state temperature is achieved. Fuel concentration distribution within the domain is well dispersed. The distribution of oxygen however shows near total consumption as the presence of oxygen is only observed in like 20% of the domain length. Comparing nanofuel combustion to fuel combustion, the steady state concentration of products in the former case is higher. Temperature is also higher with about 13%. Fuel concentration distribution is higher, but oxygen concentration distribution differences are negligible. The results reflect higher heat generation in nanofuel combustion. The results show that the use of nanofuel can lead to better fuel efficiency, faster and complete combustion, and less formation of pollutants.

References

[1] Gan, Y. and Qiao, L. Combustion characteristics of fuel droplets with addition of nano and micron-sized aluminium particles. Combustion and Flame, vol. 158, pp. 354–368, 2011.
[2] Mehta, R. N., Chakraborty, M. and Parikh, P. A. Nanofuels: Combustion, engine performance and emissions, Fuel, vol. 120, pp. 91–97, 2014.
[3] Yetter, R.A., Risha, G.A. and Son, S.F. Metal particle combustion and nanotechnology. Proceedings of the Combust Inst, vol. 32, pp. 1819-38, 2009.
[4] De Luca, L. T., Galfetti, L., Severini, F., Meda, L., Marra, G., Vorozhtsov, A. B., Sedoi, V. S. and Babuk, V. A. Combustion of composite solid propellants with nanosized aluminium. Combustion, Explosion & Shock Waves, vol. 41, pp. 680–692, 2005.
[5] Basu, S. and Miglani, A. Combustion and heat transfer characteristics of nanofluid fuel droplets: A short review, International Journal of Heat and Mass Transfer, vol. 96, pp. 482–503, 2016.
[6] Sonawane, S, Patankar, K, Fogla, A, Puranik, B, Bhandarkar, U. and Kumar, S. S., An Experimental investigation of thermo-physical properties and heat transfer performance of Al2O3-Aviation turbine fuel nanofluids. Applied Thermal Engineering, vol. 31. No. 201, pp. 2841–849, 2011.
[7] Tyagi, H., Phelan, P. E. and Prasher, R. Increased Hot -plate Ignition Probability for Nanoparticle –Laden Diesel Fuel. Nano Letters, vol. 08, pp. 1410-1416, 2009.
[8] Sajeevan, A. C., Sajith,V. Diesel Engine Emission Reduction Using Catalytic Nanoparitcles: An Experimental Investigation, Journal of Engineering, Article ID 589382, 2013.
[9] Peters, N. Laminar diffusion flamelet models in non-premixed turbulent combustion. Prog. Energy Combust. Sci., vol. 10, pp. 319-339, 1984.
[10] Poinset, T. and Veynante, D. Theoretical and Numerical Combustion, 2nd Ed., R.T. Edwards. Inc., Philadelphia, USA, 2005.
[11] Kotake, S And Hijikata, K. Numerical simulations of heat transfer and fluid flow on a personal computer, Elsevier Science Publishers B. V., Amsterdam, The Netherlands, 1993.
[12] Brinkman, H. C. The viscosity of concentrated suspensions and solutions, Journal of Chemical Physics, vol. 20, No. 4, pp. 571-581, 1952.
[13] Mintsa, H. A., Roy, G., Nguyen, C. T. and Doucet, D. New temperature dependent thermal conductivity data for water-based nanofluids. International Journal of Thermal Sciences, 48(2), pp. 363-371, 2009.
[14] Petrou, A. L., Rouli, M and Tampouris, K. The use of the Arrhenius equation in the study of deterioration and of cooking of foods and some scientific and pedagogic aspects, Chemistry Education: Research and Practice in Europe, vol. 3, No. 1, pp. 87-97, 2002.
[15] Patankar, S.V. Numerical heat transfer and fluid flow. Series in Computational Methods in Mechanics and Thermal Sciences, Hemisphere Publishing Corporation, USA, 1980.
[16] Versteeg, H. K. and Malalasekera, W. An introduction to computational fluid dynamics: The finite volume method, Pearson Education Ltd, Harlow, England, 2007.