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Ferrofluid droplet vaporization under very large magnetic power: Effects of pressure and effective thermal conductivity of liquid

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Abstract

The aim of current analysis is to quantify the influence of the effective thermodynamic and transport coefficients and of the transient process of mass and energy accumulation in the gas phase (pressure effect) on the heating and vaporization of a single ferrofluid droplet. Ferrofluids under external alternating magnetic field heat up themselves due to the magnetic Brownian relaxation mechanism. Under the condition of very large magnetic power compared to the thermal power provided by heat transfer from the gas phase, the magnetic heat source together with the heat transfer from the gas phase impose a thermal boundary layer adjacent to the droplet surface in the liquid side and the temperature presents a maximum inside the droplet, not at the surface. Since the transport coefficient increases significantly with a dispersion of a small quantity of nanoparticles, the heat transfer from the thermal boundary layer to the droplet core increases. Then the temperature of that region increases faster comparing to the case without nanoparticle dispersion. The temperature inside the thermal boundary layer increases slower because of the heat transfer to the droplet core as well as to the droplet surface. Therefore, the boiling condition which is found inside the thermal boundary layer is reached later when considering effective thermal conductivity. The droplet vaporization rate is augmented by the heat transfer from the thermal boundary layer to the droplet surface. In addiction, the strong dependence of the magnetic relaxation mechanism on temperature imposes a dependence of the vaporization rate on the initial condition of the problem.

Keywords: Ferrofluid; Magnetic relaxation heating; Magnetic nanoparticle; Droplet combustion

1. Introduction

Addition of non-magnetic and magnetic nanoparticles in fuels (nanofluid and ferrofluid) have opened a wide perspective in combustion [1–8]. Despite nanofluid fuels have received attention by the combustion community in the last decade,

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there are still issues to be clarified [9]. However, fundamental studies of ferrofluids on combustion are extremely recent comparatively to nanofluids [10–12]. Then practically all issues related to ferrofluid demand understanding. This work analyzes the influence of pressure and effective thermodynamic and transport coefficients of liquid on the heating and vaporization of a single ferrofluid droplet under an external alternating magnetic field.

The presence of nanoparticles in liquid improves all processes which are dependent on the heat transfer and provides new mechanisms of energy generation [13]. Some studies report that addition of nanoparticles in fuels leads to shorter ignition delays, reduction in heating and burning time, and more efficient combustion than traditional liquid fuels [1,2,14–18]. For instance, the addition of 0.1% nanoparticles (Al_2O_3) to Diesel fuel can improve the combustion features of the spray, leading to lower CO emission levels [6].

Recently, the magnetic property of nanoparticles is used to heat ferrofluids (magnetic relaxation heating) and applied on medical treatment of cancer [22,23]. This magnetic heating process is been analyzed theoretically to apply in droplet combustion.

The magnetic nanoparticles in ferrofluids act as a heat source in the presence of an alternating magnetic field [24–27]. Based on that, the application of magnetic relaxation heating, under the hypothesis of high magnetic power, in a ferrofluid fuel droplet was analyzed in previous works [10–12]. The first of them considered only the magnetic Brownian relaxation mechanism for the droplet heating, neglecting the heat transfer from the gas phase [10]. Since uniform nanoparticles distribution was considered, the droplet was heated up uniformly. The results pointed out to a reduction on the droplet heating time which is proportional to the reciprocal of the magnetic power. Later, that work was extended considering the heat transfer from the gas phase. Then, the combination of the magnetic relaxation heating and the heat flux from the gas phase imposes a thermal boundary layer in the liquid side, adjacent to the droplet surface [11]. The results showed temperature inside the thermal boundary layer to increase faster than that in the droplet core. In addition, the temperature close to the droplet surface in the liquid phase decreases due to the vaporization. Consequently, the temperature profile presents a local maximum inside the thermal boundary layer. Because of that, the boiling condition is found inside the droplet rather than at the droplet surface. A direct consequence of the magnetic relaxation heating is a reduction in the heating time and an increase of vaporization rate of the droplet. Also, these droplet properties are directly dependent on the frequency of the magnetic field.

The same behavior for the temperature profile of a single ferrofluid droplet under the condition of very large magnetic power had already been observed during the heating of an irradiated pure fuel droplet by high intensity laser beam [19–21].

After those two studies, the heating and vaporization model for ferrofluid droplet was extended even more to consider the combustion regime [12]. The results showed that the droplet combustion was influenced only by the improvement on the heating and vaporization of the droplet.

In the current work, the heating and vaporization problem of a single ferrofluid droplet is analyzed under the same conditions previously considered, except that now the dependence of the thermodynamic and transport coefficients on the nanoparticles volume fraction is addressed. Also, the effect of the pressure on the droplet problem is determined.

2. Model formulation

In the present work, the processes in the liquid and the gas phase are considered spherically symmetrical, since the ferrofluid fuel droplet is in a quiescent atmosphere [28,29]. In this analysis, a possible deformation of the droplet by the magnetic field will not be considered [30,31]. In the liquid phase, the presence of nanoparticles results in effective properties, e.g., specific heat $c_{l_{eff}}$ and density ρ_{eff} [32]

$$c_{l_{eff}} = (1-\phi)c_l + \phi c_n, \quad \rho_{eff} = (1-\phi)\rho_l + \rho_n, \tag{1}$$

in which ϕ is the nanoparticle volume fraction. The subscripts l and n stand for the properties relative to fluid and nanoparticle, respectively. About the effective thermal conductivity, it is known that liquid molecules close to nanoparticle surface form layered solid-like structures (nanolayer). Then the thermal conductivity of the nanolayer is in an intermediate value between that of solid and liquid. The effective thermal conductivity k_{eff} is expressed by the modified Maxwell equation [33,34],

$$k_{eff} = k_l \left[\frac{k_n + 2k_l + 2\phi(k_n - k_l)(1+\beta)^3}{k_n + 2k_l - \phi(k_n - k_l)(1+\beta)^3} \right] \tag{2}$$

in which β is the ratio of the nanolayer thickness to the nanoparticle radius.

In this analysis, the hypothesis of nanoparticles escaping from the droplet surface during the vaporization is considered. This condition is found when the boiling temperature of the carrier fluid is different from that of the surfactant added to the nanoparticle [7]. Then, the condition of constant nanoparticle volume fraction is justified during the vaporization process. Hence, the