

HEATING OF NANOFLUID DROPLET BY HIGH TEMPERATURE AMBIENT AND MAGNETIC FIELD

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Abstract. *This work considers the heating process of nanofluids droplet process of nanofluids droplet. The droplet is taken to an ambient atmosphere with high temperature and with an altering magnetic field. Under these conditions, the heating process on the droplet is due to the heat conduction from the gas-phase and the friction of the nanoparticles rotation in the liquid-phase (Viscous dissipation). The viscous dissipation is produced by the liquid-phase resistance to the nanoparticles rotation to align with the magnetic field. Once the magnetic field is removed, the Brownian movement of the liquid-phase molecules is responsible to disorder the nanoparticles alignment. The cicly is repeated applying again the magnetic field. This is the heating magnetic process in fluids with nanoparticles. The cicly is repeated applying again the magnetic field. This is the heating magnetic process in nanofluids. The proposed model identifies heating regime produced by high magnetic energy.*

Keywords: *Nanofluid, Droplet, Magnetic Power*

1. INTRODUCTION

Efficient burning of liquid fuel occurs only after the atomisation. The break down of the liquid pockets in very small droplets provides the control to the vaporisation process. Since vaporisation is controlled by the heat transfer from the gas phase to the liquid phase and the temperature gradient is practically unchanged, then the vaporisation is specified by the interphase area between the phases (Faeth, 1977; Law, 1982). The presence of nanoparticles in liquid fuels and of a varying magnetic field provide an additional heat source to fasten the droplet heating and to increase the vaporisation rate, the friction (viscosity) between the nanoparticles and the liquid. The magnetic dipole characteristic of certain nanoparticles is aligned with the external magnetic field, this process makes the nanoparticles to rotate inside the liquid. This movement of the nanoparticles against the attraction force of the liquid molecules causing friction, a source of heat, process called magnetic hyperthermia (Rosensweig, 2002).

The magnetic hyperthermia is already used as a technique to destroy cancer cell (Maenosono and Saita, 2006). In this work, the viscous dissipation generated by the rotation of nanoparticles will be used to heat a droplet. In order to evidence of the heating magnetic process, the magnetic power will be considered much higher than the thermal power produced by the conduction process from the gas phase to the liquid phase.

2. MATHEMATICAL FORMULATION

By considering the droplet spherical with initial ($t = 0$) radius \bar{a}_0 , density ρ_l , specific heat c_l and thermal conductivity k_l . The substance of the liquid phase has low volatility, i.e. the vaporisation begins when the temperature is very close to the boiling temperature. In these conditions, the heating process of the droplet occurs practically at the initial constant radius. The energy conservation of the liquid phase (Maenosono and Saita, 2006,).

$$\rho_l c_l \frac{\partial T}{\partial t} = k_l \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) + \pi \mu_0 \chi_0 H_0^2 \bar{f} \frac{2\pi \bar{f} t_m}{1 + (2\pi \bar{f} t_m)^2} \quad (1)$$

The last term in Eq. (1) represents the energy source due to the response of the nanoparticles to the magnetic field. The magnetic constants are: the magnetic permeability μ_0 ($= 4\pi 10^{-7} T.m/A$), the magnetic susceptibility χ_0 , the magnetic field amplitude H_0^2 and frequency \bar{f} . The relaxation time t_m is given by (Rosensweig, 2002).

$$t_m \equiv \frac{3\mu V_H}{k_B T}, \quad (2)$$

in which V_H is hydrodynamic volume of nanoparticle, k_B is the Boltzmann constant, $1.3810^{-23} J/K$, T is the temperature and μ is the dynamic viscosity of fluid. The hydrodynamic volume V_H is (Rosensweig, 2002).

$$V_H \equiv \frac{\pi(D + 2\delta)^3}{6}. \quad (3)$$

D and δ are the nanoparticle diameter and the ligand layer thickness, respectively.

The droplet is at an ambient with temperature T_∞ , density ρ_∞ and pressure p_∞ . The thermodynamic and transport coefficients of the ambient gas phase are: specific heat at constant pressure c_p and thermal conductivity k_g .

To handle properly the problem, the liquid phase energy conservation equation is normalized using the following definitions

$$\tau \equiv t/t_{vap}, \quad x \equiv r/\bar{a}_0, \quad \theta \equiv T/T_\infty.$$

The time $t_{vap} \equiv (\bar{a}_0^2/\alpha)(\rho_l/\rho_\infty)$ is an estimative of the droplet vaporisation time if only the heat conduction from the gas phase were responsible for the heating process (Fachini, 1999). Equation (1) in the nondimensional form is

$$\frac{\partial \theta}{\partial \tau} = A \nabla^2 \theta + P_m \frac{f \theta}{\theta^2 + f^2}, \quad (4)$$

in which $A \equiv c_p k_l / c_l k_g$, $f \equiv 2\pi \bar{f} t_m^*$ and

$$P_m \equiv \pi \mu_0 \chi_0 H_0^2 \bar{f} \frac{1}{\rho_l c_l T_\infty} \frac{\bar{a}_0^2}{\alpha} \frac{\rho_l}{\rho_\infty}. \quad (5)$$

The relaxation time t_m^* is computed for the ambient temperature, $t_m^* \equiv (3\mu V_H)/(k_B T_\infty)$

The nondimensional boundary conditions and initial condition are:

$$\left. \frac{\partial \theta}{\partial x} \right|_{x=0} = 0, \quad x^2 \left. \frac{\partial \theta}{\partial x} \right|_{a^+} - \frac{k_l}{k_g} x^2 \left. \frac{\partial \theta}{\partial x} \right|_{a^-} = \lambda l, \quad (6)$$

$$\theta = \theta_0, \quad x < a, \quad \tau = 0 \quad (7)$$

The nondimensional vaporisation rate λ is $\dot{m} c_p / (4\pi \bar{a}_0 k_g)$ and the latent heat l is $L/(c_p T_\infty)$

In this work, the hypothesis of very low volatile liquid is considered, therefore the droplet heating is proceeded practically with negligible vaporisation and constant droplet radius. Also, the magnetic power is considered much larger than the thermal conduction from the the gas phase, then $P_m \gg 1$. Under the condition of very high magnetic power, Eq. (4) can be written, in first approximation,

$$\frac{\partial \theta}{\partial \tau} = P_m \frac{f \theta}{\theta^2 + f^2}, \quad (8)$$

whose solution is

$$P_m \tau = \frac{\theta^2 - \theta_0^2}{2f} + f \ln \left(\frac{\theta}{\theta_0} \right) \quad (9)$$

For the cases with very low frequency, $f \ll 1$, the droplet heating is proportional to the square root to the time

$$\theta \sim (\theta_0^2 + 2f P_m \tau)^{1/2} \quad (10)$$

The model represented by Eq. (10) is valid to describe the droplet temperature evolution provided $f P_m \gg 1$. The condition of $f \equiv \bar{f} t_m^* \ll 1$ means that the characteristic time of the magnetic field variation is much larger than the characteristic time of desorganizing the dipoles intrinsic of each nanoparticle produced by the collision between the nanoparticles and the molecules of the substance that forms the droplet. Then, the droplet heating exclusively by the energy dissipation generated by the rotation of the nanoparticles aligning with the magnetic field occurs when the magnetic power is such that satisfies $P_m \gg 1/f$. The heating time can be computed imposing θ_B (boiling temperature) at $\tau = \tau_h$, which leads to $\tau_h = (\theta_B^2 - \theta_0^2)/(2f P_m) \sim (\theta_B - \theta_0)/(f P_m)$, use was made of $\theta_B + \theta_0 \sim 2$. Since $\theta_B - \theta_0 = O(1)$, the order of the magnitude of the modified heating time is $P_m \tau_h = O(1/f)$.

In the other hand, for very large frequency, $f \gg 1$, the droplet heating is described by

$$\theta \sim \theta_0 \exp(P_m \tau / f) \quad (11)$$

When the frequency of oscillation of the magnetic field is large, the magnetic power P_m must be large but not so large as previous case, it is necessary to have condition $P_m \gg f$. The magnetic field will pass by many cicly, but the number of collisions of the nanoparticles with the molecules is not large enough to desorganize the direction of the dipoles. Therefore, in each cicly the rotation of the nanoparticles is very limited and the quantity of energy provided to the fluid due to the viscous dissipation is small. The modified heating time for the cases in which $P_m \gg f \gg 1$ is calculated as $\tau_h = f \ln(\theta_B/\theta_0)/P_m \sim f(\theta_B - \theta_0)/P_m$, use was made of $\theta_0 \sim 1$. As mentioned above $\theta_B - \theta_0 = O(1)$, the order of magnitude of the heating time is $P_m \tau_h = O(f)$

Either $f \ll 1$ or $f \gg 1$, the modified heating time is $P_m \tau_h \gg 1$. As the model is valid provided $P_m \gg 1$, the heating time τ_h is very small.

The modified heating time of the droplet computed from Eq. (9) with $\theta = \theta_B$ at $\tau = \tau_h$ is as following

$$P_m \tau_h = \frac{\theta_B^2 - \theta_0^2}{2f} + f \ln \left(\frac{\theta_B}{\theta_0} \right) \quad (12)$$

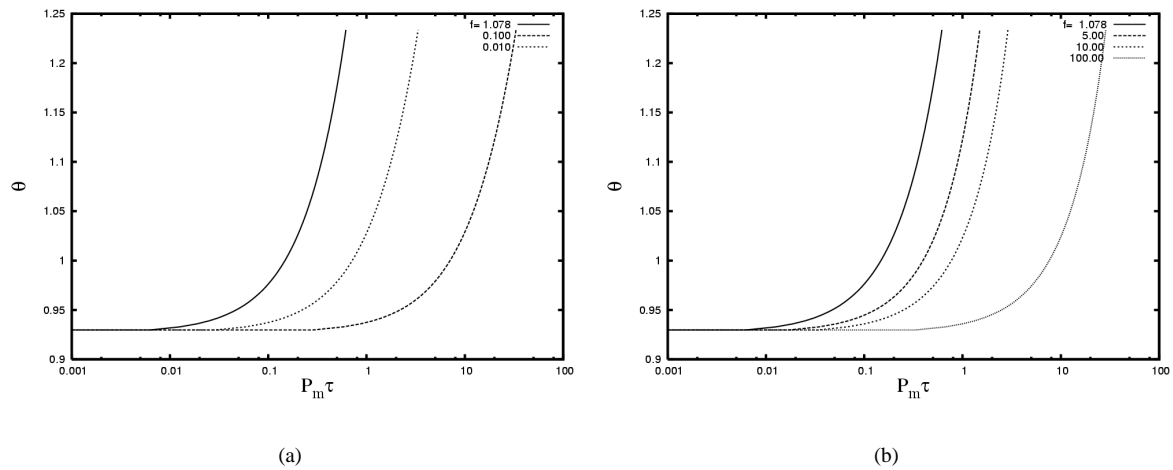


Figure 1. Evolution of the droplet temperature θ for different values of the nondimensional magnetic field frequency f ; a) 10^{-2} , 10^{-1} and 1.078, b) 1.078, 5, 10 and 10^2 .

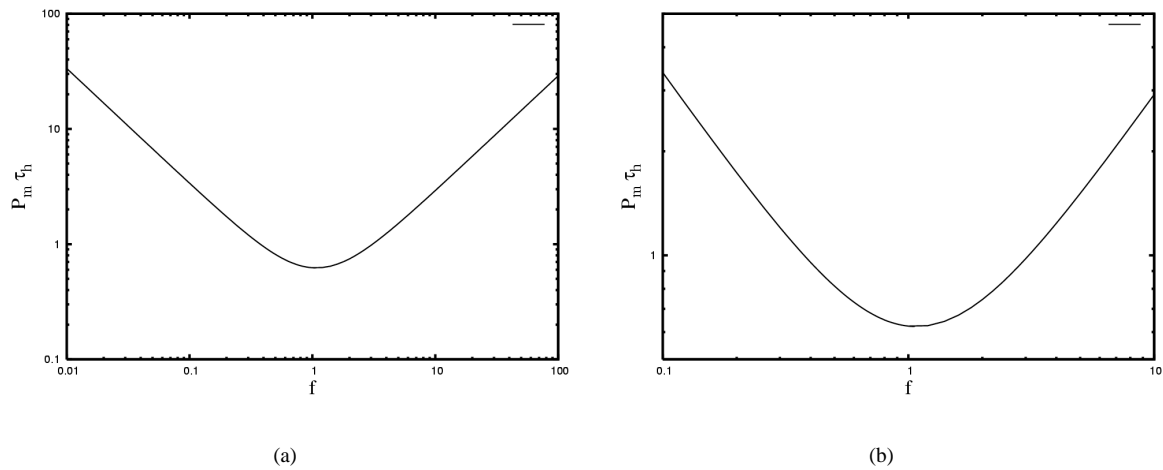


Figure 2. The heating time defined as $P_m \tau_h$ as a function of the frequency f .

Equation (12) shows the heating time is as function primary of the frequency f and secondary of the other two properties, the boiling and the initial droplet temperatures, θ_B and θ_0 . The minimum heating time is found by $d(P_m \tau_h)/df = 0$, which leads to the frequency value given by

$$f = \left[\frac{\theta_B^2 - \theta_0^2}{2 \ln(\theta_B/\theta_0)} \right]^{1/2} \quad (13)$$

For the cases $\theta_B - \theta_0 = o(1)$ and supposing $\theta_B = \theta_0 + \Delta$ ($\Delta = o(1)$), an estimation of the frequency can be found,

$$f \sim \theta_0^{1/2} (1 + 3\Delta/4\theta_0) \quad (14)$$

3. RESULTS

To test the model, Eq. (9), n-heptane is considered the substance in the droplet; then the boiling temperature is $T_B = 371K$. The droplet is in an ambient atmosphere in which the temperature is imposed as $T_\infty = 300K$. The initial temperature of the temperature is taken equal to the ambient.

Figure 1 shows the several heating history of the droplet depending on the frequency. On plots 1.a and 1.b, the low and high frequencies effects are highlighted; for the lowest and the highest conditions the heating time is large ($P_m \tau_h \sim 30$). For conditions one order of magnitude higher and lower, respectively, the heating time is about unity. The frequency

$f = 1.078$ corresponds to the minimum heating time $P_m \tau_h = 0.622$, as shown in Fig. 2. Note that maximum effect of the magnetic power is not on the frequency $f = 1$, the deviation is caused by the fuel properties, represented by the boiling temperature, and the ambient condition, represented by the ambient temperature.

To observe clearly the effect of the frequency, Fig. 2 is depicted. This plot exhibits the minimum heating time for the frequency close to unity, $f = 1.078$. By comparing the two sides of $f = 1$, it is seen that the heating process is slightly faster for $f > 1$. As seen in Fig. 2.b, the data on the right branch are below the data on the left branch, which means modified heating time $P_m \tau_h$ in the right side smaller than that on the left side..

4. CONCLUSION

For non magnetic, non nanofluids combustible, the improve on the vaporisation rate means increases the liquid-vapour interphase area and for reaching this goal, it is necessary to increase the liquid fuel atomisation. However, as shown in this paper, magnetic nanofluids combustible can be an alternative solution for improving the vaporisation rate of fuels. The results of this analysis show that the heating process has a maximum effect for frequencies around $f = 1$. The present work is valid only for very high magnetic power. Future works will consider magnetic power of order unity.

5. ACKNOWLEDGEMENTS

The author is thankful for MSc Nelio Sasaki who presented the basic papers on heating magnetic fluid. This paper is partially support by CNPq (Proc No. 563835/2008-7).

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