# Temperature effects on formation of a uniform layer of isotopes inside a cryogenic ICF target

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The steady-state motion of a gas bubble inside a non-isothermal, spherical, liquid filled cryogenic target is investigated by taking into account the effects of gravity, the thermally induced gradient of the gas-liquid interfacial tension and the finite size of the liquid container. The net result is an expression for the temperature gradient at the target exterior, which will sustain a uniform liquid layer of hydrogen isotopes inside an ICF target. A simple model was established on the basis of the calculation and analysis above.

## INTRODUCTION

An optimal configuration for ICF targets is a spherical shell containing a uniform layer of fusion fuel condensate on the interior surface. Such targets, in particular those containing a thick fuel layer, are difficult to fabricate because the fuel sags due to gravity, thus making the condensate layer thicker at the bottom of the target than at the top [1].

The non-contact thermal gradient method [2] is one such technique that is designed to counteract the gravity induced fuel sagging. This technique employs a vertically imposed temperature gradient across the target. In particular, the magnitude and direction of this gradient are chosen such that the thermally induced migration of the liquid fuel may precisely counterbalance its slumping due to gravity, bringing about a uniform liquid fuel layer on the inner surface of the target.

The purpose of this work is to study the steady-state motion of a gas bubble inside a spherical micro-shell under the influence of gravity, a thermally induced gradient of gas-liquid interfacial tension, and the finite size of the micro-shell--a situation frequently encountered in fabricating high-compression inertial confinement fusion (ICF) targets.

## THEORY

To conveniently describe the thermally induced behavior of hydrogen isotopes inside a spherical ICF target, the system under investigation is divided into four regions. Starting from the innermost region they are the fuel vapor, liquid, spherical glass shell (SGS), and helium gas regions, and all considered concentric spheres. The helium exchange gas envelope responsible for cooling the target is assumed to be quiescent.

Both the vapor and liquid of the hydrogen isotopes are assumed to be Newtonian and incompressible. The flow fields are assumed to be laminar, and azimuthally symmetric. The thermodynamic and transport properties, namely, density, viscosity and thermal conductivity are defined at average target temperature, which is nearly the temperature at the target equator since the temperature gradient across the target is linear and in the vertical direction. Also we assume that there is no mass transfer between the liquid and the gas. Another assumption is that the bubble has already attained its terminal velocity when it becomes concentric with the micro-shell.

Calculation about the fuel thickness of ICF target

According to the mass conservation in cryogenics target, the total mass in the cryogenic target is constant whether the status of the fuel is liquid or gas. When the infilling processing is completed, the whole mass in cryogenic target is

$$\rho_f V_0 = \rho_l(T)V_c + \rho_g(T)V_g \tag{1}$$

where $\rho_f$ is the density of the initial gas. $\rho_l(T)$ and $\rho_g(T)$ are respectively densities of condensed and saturated vapor fuel. $V_0, V_c, V_g$ are total volume, the condensed and the saturated vapor volume in the target, respectively.

If $\delta$ =W/R, here $R$ and $W$ is respectively the inner radius and the fuel thickness of the target, then

$$\rho_f = \rho_l(T)\left[1-(1-\delta)^3\right] + \rho_g(T)(1-\delta)^3 \tag{2}$$

It is obviously that when the initial gas density and the temperature $T$ are constant, we can get the $\delta$, then the thickness of fuel in target. To demonstrate this relation more clearly, we figure out the relation curve between the relative volume of vapor bubble and temperature of normal hydrogen (see Figure 1).

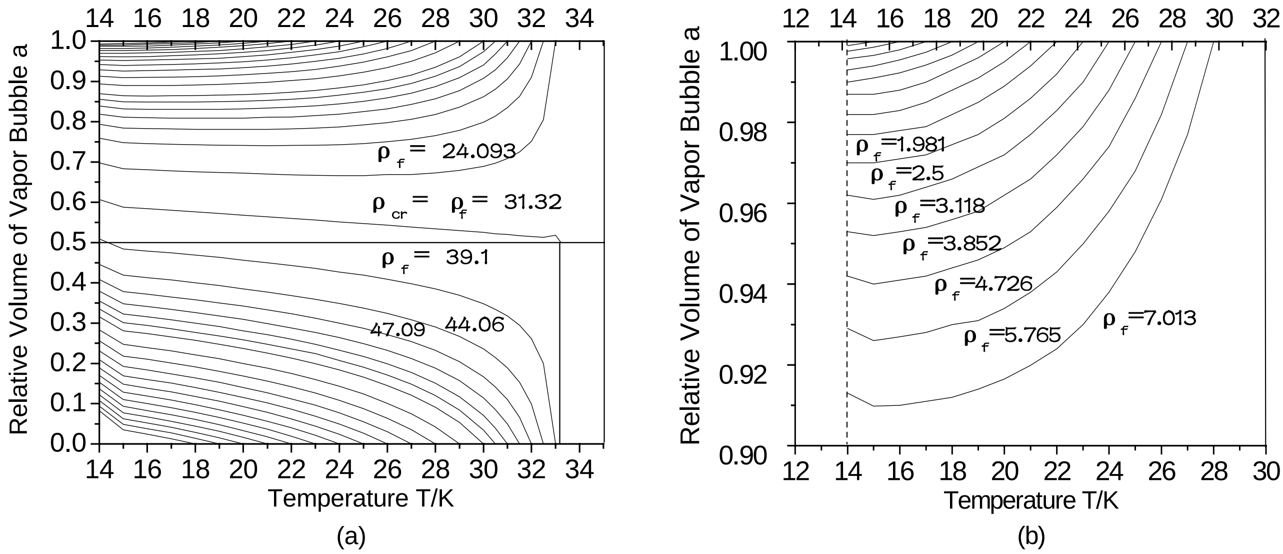


Figure2 The relation curve between relative volume of vapor bubble and temperature of normal hydrogen( $\rho_f$ g/cm$^3$)

Governing equations of fluid field

Since the fluid flows are azimuthally symmetries, in terms of the Stokes stream function $\psi$ defined as $\upsilon_r = (-1/r^2\sin\theta)\partial\psi/\partial\theta$, and $\upsilon_\theta = (1/r\sin\theta)\partial\psi/\partial r$, the low Reynolds number approximation of the fluid equation in the spherical coordinate system is

$$E^2(E^2\Psi_l)=0 \quad \text{and} \quad E^2(E^2\Psi_g)=0 \tag{3}$$

where

$$E^2 = \frac{\partial^2}{\partial r^2} + \frac{\sin\theta}{r^2}\frac{\partial}{\partial\theta}\left(\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\right), \quad r = \tilde{r}/R_B, \quad \psi = \tilde{\psi}/(R_B V_{ref}),$$

$V_{ref}$ is the reference velocity, and $R_B$ is the radius of the gas bubble. The title denotes that the variables are expressed in real units, $\upsilon_r$ and $\upsilon_\theta$ are the r component and the $\theta$ component of the flow respectively. The general solution to Eq.(3) also can be obtained in terms of the Happel & Brenner [3].

At $r = b^{-1}$: $\upsilon_{r,l} = -U\cos\theta$ , $\upsilon_{\theta,l} = U\sin\theta$,

where U is the steady-state velocity of the bubble, $b = R_B/R$.

at $r = 1$: $\upsilon_{r,l} = \upsilon_{r,g} = 0$ , $\upsilon_{\theta,l} = \upsilon_{\theta,g}$ and $\mu_l\left[\frac{1}{r}\frac{\partial V_{r,l}}{\partial\theta} + \frac{\partial V_{\theta,l}}{\partial r} - \frac{V_{\theta,l}}{r}\right] - \mu_g\left[\frac{1}{r}\frac{\partial V_{r,g}}{\partial\theta} + \frac{\partial V_{\theta,g}}{\partial r} - \frac{V_{\theta,g}}{r}\right] = -\frac{\partial\gamma_{gl}}{\partial\theta}$

where $\mu$ is the viscosity of the fluids, and the $\gamma_{gl}$ is the gas-liquid interfacial tension.

at $r = 0$: $\psi_g(0,\theta)$ is finite.

Following Haberman & Sayre (1950) [4], the drag force on the bubble is given by

$F_d = -4\pi\mu_l R_B D_n\big|_{n=2}$ , then

$$G_g + F_d + F_b = 0 \tag{4}$$

where $G_g$, $F_b$ respectively stand for the weight and buoyancy forces.

After a straightforward, yet tedious, algebra, the expression for the steady-state velocity U of the bubble is obtained as

$$U = \left[\frac{2}{3\mu_l}\frac{R_B{}^2(\rho_c - \rho_g)g}{K_2} - \frac{1}{6}I_2(2 - 5b^3 + 3b^5)\right][3 + 2\sigma - 3(1-\sigma)b^5]^{-1} \tag{5}$$

where $\sigma = \mu_l / \mu_g$ .

The function $I_2$ in (5) represents the effect of the interfacial tension gradient on the velocity of the bubble. Because the interfacial tension gradient results from the non-isothermal temperature field, if the temperature gradient across the target is conformed, the $I_2$ then can be estimated as follow:

$$I_2 = -\frac{3}{\mu_g}\int_0^{\pi}\frac{\partial\gamma_{gl}}{\partial\theta}\sin^2\theta\, d\theta$$

also the velocity of the bubble can be gotten.

<u>Governing equations of temperature field</u>

Due to the fact that Reynolds numbers of the liquid and gas flows are low and that the Prandtl number for liquid hydrogen is approximately unity, which allows one to ignore the convection term in the heat equation and therefore, reduces the heat equation for the fluids to

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)T = 0 \tag{6}$$

This is an exactly the Laplacian equation.

According to the continuities of the temperature fields:

At $r = d^{-1}$ $T_W(\frac{1}{d},\theta) = T_{ext}(\theta)$; at $r = b^{-1}$ $T_W(\frac{1}{b},\theta) = T_l(\frac{1}{b},\theta)$; at r=1 $T_l(1,\theta) = T_g(1,\theta)$; at r=0,

$T_g(0,\theta)$ is limited, where $d = R_B/R_0$, $R_0$ is the outer radium of the target.

Also according to the condition of the heat fluxes:

At r=1, $k_l\frac{\partial T}{\partial r}\Big|_{r=1} = k_g\frac{\partial T}{\partial r}\Big|_{r=1}$; at $r = b^{-1}$, $k_w\frac{\partial T}{\partial r}\Big|_{r=\frac{1}{b}} = k_l\frac{\partial T}{\partial r}\Big|_{r=\frac{1}{b}}$

Then we can get the temperature field of the target.

## DISCUSSIONS

Let the temperature field on the outer surface of the spherical shell be specified as

$$T_{ext}(\theta)=T_0+R_0\sum_{n=1}^{\infty} t_n P_n(\cos\theta) \tag{7}$$

We note that for a small temperature change across the target, the interfacial tension can be expressed as a linear function of the temperature T at the liquid-gas interface:

$$\gamma(T)=\gamma_0+\gamma_1 T \tag{8}$$

where $\gamma_0$ is the interfacial tension at some reference temperature and $\gamma_1$ is a constant. The constant $\gamma_1$ represents the magnitude of the rate of change in surface tension with respect to temperature.

Therefore $I_2$ can be evaluated analytically, and the temperature gradient needed to hold a bubble stationary is

$$(t_1)_s=-\frac{2}{3}\frac{N_2-d^3}{N_2-b^3}\frac{\left[1+2\varepsilon_1-(1-\varepsilon_1)b^3\right]}{\varepsilon_1\sigma K_2(2-5b^3+3b^5)}\frac{R_B(\rho_l-\rho_g)g}{\gamma_1} \tag{9}$$

## CONCLUSIONS

The steady-state migration velocity of a gas bubble located at the center of a spherical shell has been calculated by considering the combined effect of gravity, interfacial tension gradient, and the finite size of the shell. An analytical expression for the temperature gradient that will sustain a stationary bubble at the center of the spherical shell has been derived. Also a calculating function relation about liquid $H_2$ thickness of cryogenic target is proposed using the mass conservation in cryogenic target. The analytic method for the model is also fit for the $D_2$, $T_2$ or the mixture of the D-T.

It must be pointed out that the present work does not include the corresponding release and absorption of heat in the processes of condensation and evaporation, also not consider the isotope effects such as the differences in the thermodynamic properties and transport coefficients of the isotopic species. A theory intended to include factors above is currently being formulated and will be reported in a future publication.

## ACKOWNLEGEMENT

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