Journal of the Korean Crystal Growth and Crystal Technology
Vol. 20, No. 3 (2010) 125-132

Influence of thermo-physical properties on solutal convection by physical vapor transport of Hg_2Cl_2-N_2 system: Part I - solutal convection

Geug-Tae Kim[†] and Young Joo Kim*

Department of Nano-Bio Chemical Engineering, Hannam University, Daejeon 305-811, Korea
**Bioinformatics Research Center, Korea Research Institute of Bioscience and Biotechnology, Daejeon 305-806, Korea*

(Received May 11, 2010)
(Revised May 31, 2010)
(Accepted June 4, 2010)

Abstract For typical governing dimensionless parameters of $Ar = 5$, $Pr = 1.16$, $Le = 0.14$, $Pe = 3.57$, $Cv = 1.02$, $Gr_s = 2.65 \times 10^6$, the effects of thermo physical properties such as a molecular weight, a binary diffusivity coefficient, a partial pressure of component B on solutally buoyancy-driven convection (solutal Grashof number $Gr_s = 2.65 \times 10^6$) are theoretically investigated for further understanding and insight into an essence of solutal convection occurring in the vapor phase during the physical vapor transport of a Hg_2Cl_2-N_2 system. The solutally buoyancy-driven convection is significantly affected by any significant disparity in the molecular weight of the crystal components and the impurity gas of nitrogen. The solutal convection in a vertical orientation is found to be more suppressed than a tenth reduction of gravitational accelerations in a horizontal orientation. For crystal growth parameters under consideration, the greater uniformity in the growth rate is obtained for either solutal convection mode in a vertical orientation or thermal convection mode in horizontal geometry. The growth rate is also found to be first order exponentially decayed for $10 \le P_B \le 200$ Torr.

Key words Mercurous chloride, Solutal convection, Nitrogen and physical vapor transport (PVT)

1. Introduction

Mercurous chloride (Hg_2Cl_2) materials are important for applications in acousto-optic and opto-electronic devices such as Bragg cells, X-ray detectors operating at ambient temperature [1]. In general, single crystal of Hg_2Cl_2 can be grown in sealed ampoules by the physical vapor transport (referred as PVT hereafter) based on a sublimation-condensation mechanism. Convection inevitably occurs in the vapor phase during the PVT due to a thermal gradient between the source and the crystal region and, thus induces problems ranging from crystal inhomogeneity to structural imperfection. Therefore, in order to analyze and control the PVT process accurately, and also make significant improvements in the process, it is essential to investigate the essence of convection occurring in the vapor phase during the PVT process. In particular, for the system where the molecular weight of component A is much larger than that of B,the solutally induced buoyancy-driven convection (solutal convection) becomes significantly important.

Rosenberger's research group [2] examined the effects of convection during the PVT process inside vertical cylindrical enclosures for a time-independent system, and showed that even in the absence of gravity, convection can be present, causing nonuniform concentration gradients. They emphasized the role of geometry in the analysis of the effects of convection. As such these fundamentally constitute steady state two-dimensional models. The steady state models are limited to low Rayleigh number applications, because the oscillation of the flow field occurs as the Rayleigh number increases. To address the issue of unsteady flows in PVT, Duval [3] performed a numerical study on transient thermal convection in the PVT processing of Hg_2Cl_2 for a vertical rectangular enclosure with insulated temperature boundary conditions for Rayleigh numbers up to 10^6. Nadarajah *et al.* [4] addressed the effects of solutal convection for any significant disparity in the molecular weights of the crystal components and the inert gas. Zhou *et al.* [5] reported that the traditional approach of calculating the mass flux assuming one-dimensional flow for low vapor pressure systems is indeed correct. Rosenberger *et al.* [6] studied three-dimensional numerical modeling of the PVT yielded quantitative agreement with measured transport rates of iodine through octofluorocyclobutane (C_4F_8) as inert background gas in horizontal cylindrical ampoules. More recently the systematic studies on the convective effects during the physical vapor transport of mercurous chloride materials have been performed in applications of

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[†] Corresponding author
Tel: +82-42-629-8837
Fax: +82-42-629-8835
E-mail: gtkim@hnu.kr

microgravity environments [7-17].

In this study, a two-dimensional model is used for the analysis of the PVT processes during vapor-growth of mercurous chloride crystals (Hg_2Cl_2) in horizontally oriented, cylindrical, closed ampoules in a two-zone furnace system. Diffusion-limited processes are considered in this paper, although the recent paper of Singh, Mazelsky and Glicksman [18] demonstrated that the interface kinetics plays an important role in the PVT system of Hg_2Cl_2. Solutally buoyancy-driven convection will be considered primarily for a mixture of Hg_2Cl_2 vapor and impurity of nitrogen (N_2).

It is the purpose of this paper to relate applied solutally buoyancy-driven (solutal) convection process parameters such as the gravitational acceleration and aspect ratio (transport length -to-width), and the partial pressure of component B, P_B (Torr) to the crystal growth rate and its interfacial distribution in order to gain further insights into the underlying physicochemical processes.

2. Physical and Mathematical Formulations

Consider a rectangular enclosure of height H and transport length L, shown in Fig. 1. The source is maintained at a temperature T_s, while the growing crystal is at a temperature T_c, with $T_s > T_c$. PVT of the transported component A (Hg_2Cl_2) occurs inevitably, due to presence of impurities, with the presence of a component B (N_2). The interfaces are assumed to be flat for simplicity. The finite normal velocities at the interfaces can be expressed by Stefan flow deduced from the one-dimensional diffusion-limited model [19], which would provide the coupling between the fluid dynamics and species calculations. On the other hand, the tangential component of the mass average velocity of the vapor at the interfaces vanishes. Thermodynamic equilibria are assumed at the interfaces so that the mass fractions at the interfaces are kept constant at $\omega_{A,s}$ and $\omega_{A,c}$. On the vertical non-reacting walls appropriate velocity boundary conditions are no-slip, the normal concentration gradients are zero, and wall temperatures are imposed as linear temperature gradients.

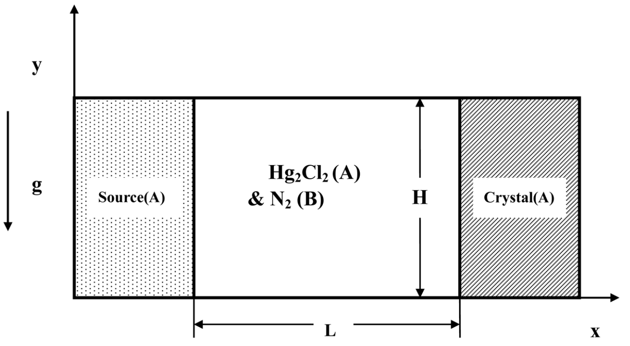

Fig. 1. Schematic of PVT growth reactor in a two-dimensional rectangular system.

Thermo-physical properties of the fluid are assumed to be constant, except for the density. When the Boussinesq approximation is invoked, density is assumed constant except the buoyancy body force term. The density is assumed to be a function of both temperature and concentration. The ideal gas law and Dalton's law of partial pressures are used. Viscous energy dissipation and the Soret-Dufour (thermo-diffusion) effects can be neglected, as their contributions remain relatively insignificant for the conditions encountered in our PVT crystal growth processes. Radiative heat transfer can be neglected under our conditions, based on Kassemi and Duval [20].

The transport of fluid within a rectangular PVT crystal growth reactor is governed by a system of elliptic, coupled conservation equations for mass (continuity), momentum, energy and species (diffusion) with their appropriate boundary conditions. Let u_x, u_y denote the velocity components along the x- and y-coordinates in the x, y rectangular coordinate, and let T, ω_A, p denote the temperature, mass fraction of species A (Hg_2Cl_2) and pressure, respectively.

The dimensionless governing equations are given by:

$$\nabla^* \bullet V^* = 0, \tag{1}$$

$$\vec{V}^* \bullet \nabla^* \vec{V}^* = -\nabla^* p^* + \Pr \nabla^{*2} \vec{V}^* - Ra \cdot \Pr \cdot T^* \cdot e_g, \tag{2}$$

$$\vec{V}^* \bullet \nabla^* T^* = \nabla^{*2} T^* \tag{3}$$

$$\vec{V}^* \bullet \nabla^* \omega_A^* = \frac{1}{Le} \nabla^{*2} \omega_A^* \tag{4}$$

These nonlinear, coupled sets of equations are numerically integrated with the following boundary conditions:

On the walls ($0 < x^* < L/H$, $y^* = 0$ and 1):

$$u^*(x^*,0) = u^*(x^*,1) = v^*(x^*,0) = v^*(x^*,1) = 0 \tag{5}$$

$$\frac{\partial \omega_A^*(x^*,0)}{\partial y^*} = \frac{\partial \omega_A^*(x^*,1)}{\partial y^*} = 0,$$

$$T^*(x^*,0) = T^*(x^*,1) = \frac{T - T_c}{T_s - T_c}$$

On the source ($x^* = 0$, $0 < y^* < 1$):

$$u^*(0,y^*) = -\frac{1}{Le} \frac{\Delta\omega}{(1 - \omega_{A,s})} \frac{\partial \omega_A^*(0,y^*)}{\partial x^*}, \tag{6}$$

$v^*(0,y^*) = 0,$

$T^*(0,y^*) = 1,$

$\omega_A^*(0,y^*) = 1.$

On the crystal ($x^* = L/H,\ 0 < y^* < 1$):

$$u^*(L/H,y^*) = -\frac{1}{Le}\frac{\Delta\omega}{(1-\omega_{A,c})}\frac{\partial\omega_A^*(L/H,y^*)}{\partial x^*}, \tag{7}$$

$v^*(L/H,y^*) = 0,$

$T^*(L/H,y^*) = 0,$

$\omega_A^*(L/H,y^*) = 0.$

In the dimensionless parameters in the governing equations the thermo-physical properties of the gas mixture are estimated from gas kinetic theory using Chapman-Enskog's formulas [21]. The vapor pressure [22] p_A of Hg_2Cl_2 (in the unit of Pascal) can be evaluated from the following formula as a function of temperature: in which a = 29.75, b = 11767.1.

$$p_A = e^{(a-b/T)}, \tag{8}$$

The detailed numerical schemes in order to solve the discretization equations for the system of nonlinear, coupled governing partial differential equations are found in [23].

3. Results and Discussion

The purposes for this study is to correlate the growth rate and its interfacial distribution to process parameters such as a gravitational acceleration, an aspect ratio, a partial pressure of component B to investigate the effects of impurity (N_2) on solutal convection during the PVT (physical vapor transport). Thus, it is desirable to express some results in terms of dimensional growth rate, however they are also applicable to parameter ranges over which the process varies in the manner given. The six dimensionless parameters, namely Gr, Ar, Pr, Le, C_v and Pe, are independent and arise naturally from the dimensionless governing equations and boundary conditions.

Because the molecular weight of impurity (N_2) is not equal to that of the crystal component (Hg_2Cl_2) during the PVT (physical vapor transport), both solutal and/or thermal effects should be considered. In this study, one examines the effect of solutal convection on the crystal growth rate and its interfacial distribution because the imposed wall temperature profile has little effect on the growth rate so that thermal convection would be negligible in comparison with solutal convection. Conductive wall boundary conditions based on a linear temperature profile are considered, while the insulated walls are not considered at this point because it is difficult to obtain in practice and most of vapor growth experiments. In addition, a nonlinear thermal profile ("hump") imposed at the walls is not considered at this point which can be obtained by an often used experimental technique to prevent undesirable nucleations [4, 24, 25]. In general, this temperature hump could eliminate the problem of vapor supersaturation along the transport path and, thus, of parasitic nucleations at the walls. But, these humps may result in sharp temperature gradients near the crystal region, inducing thermal stresses and a decrease in crystal quality.

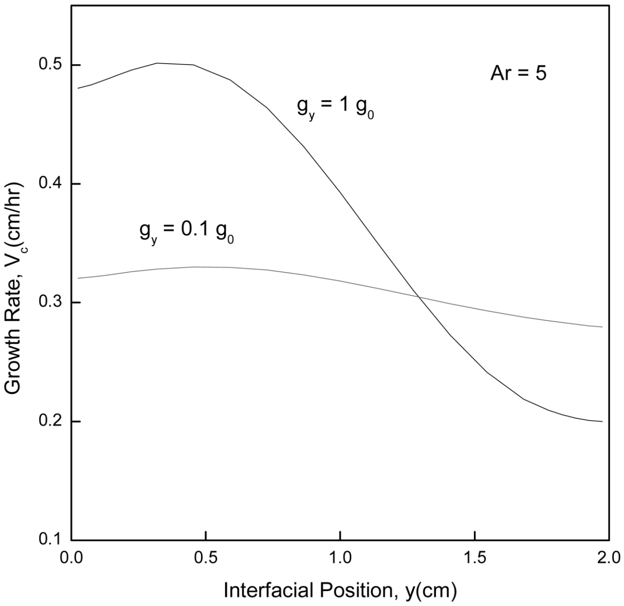

Fig. 2. Interfacial distribution of growth rates along the y-direction of the crystal surface for a horizontal ampoule of aspect ratio 5, a linear wall temperature profile between $T_s = 370.5^\circ C$ and $T_c = 358.1^\circ C$ and $g_y = 1g_0$ and $0.1g_0$.

Fig. 2 shows one's results for a horizontal system of aspect ratio 5 (L = 10 cm, H = 2 cm) with a source temperature $T_s = 370.5^\circ C$, a crystal temperature $T_c = 358.1^\circ C$, a total pressure of 737.23 Torr and a gravitational acceleration of $1g_0$ in the negative y-direction, where g_0 denotes the Earth's gravitational acceleration. The convective flow affects significantly the non-uniformities in the growth rate, which indicates the solutal convection mode is predominant over the diffusion mode. This result is consistent with the previous works [2, 4]. It can be seen that the convection enhances the overall mass transport of component A, which is directly and linearly proportional to the growth rate, but generates much both the non-uniformity and asymmetry in the growth rate. One also can see that a tenth reduction in gravitational acceleration,

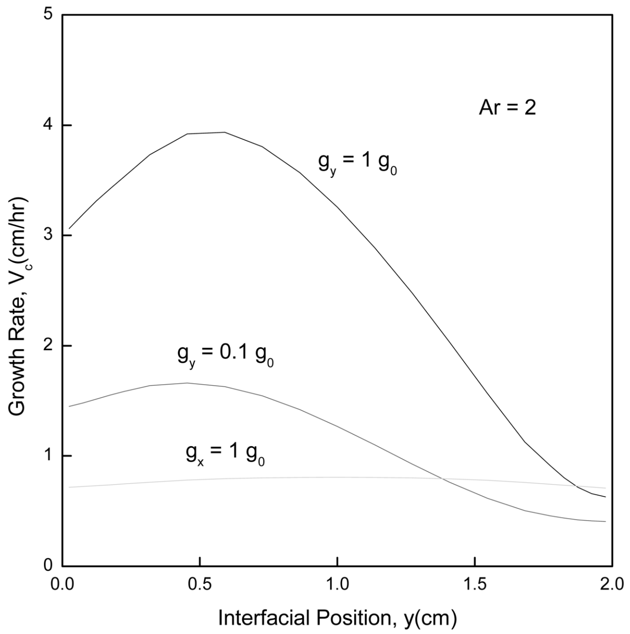

Fig. 3. Interfacial distribution of growth rates along the y-direction of the crystal surface for a horizontal ampoule of aspect ratio 2, a linear wall temperature profile between $T_s = 370.5^oC$ and $T_c = 358.1^oC$. Horizontal orientation: $g_y = 1g_0$ and $0.1g_0$. Vertical orientation: $g_x = 0.1g_0$.

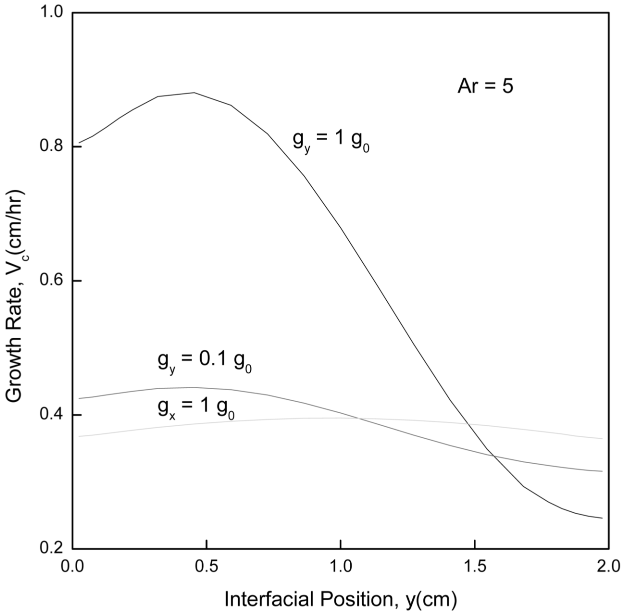

Fig. 4. Interfacial distribution of growth rates along the y-direction of the crystal surface for a horizontal ampoule of aspect ratio 5, a linear wall temperature profile between $T_s = 378.5^oC$ and $T_c = 358.1^oC$. Horizontal orientation: $g_y = 1g_0$ and $0.1g_0$. Vertical orientation: $g_x = 0.1g_0$.

$0.1g_0$ suppresses the convection. Fig. 3 shows the results for a system with same parameters as in Fig. 2 except for an aspect ratio of 2 (L = 4 cm, H = 2 cm). The growth rates are greater than for aspect ratio of 5 by one order of magnitude but the non-uniformities due to convection are also much greater. A tenth reduction of gravitational level results in a suppress of convective effects on the growth rate and, consequently leads to a decrease of 42% in the growth rate. As regards orientation against the gravity vector, the convection is more important when the ampoule is in a horizontal rather than in a vertical orientation. The maximum growth rate for the horizontal case with an acceleration of $1g_0$ is greater than that for the vertical case by a factor of 4.87, where the latter has same parameters as the former except for the orientation against the gravity vector. It can also be shown that maximum growth rates appear in the neighborhood of y = 0.5 for the horizontal system regardless of the gravitational accelerations down to $10^{-1}g_0$. Note that in the horizontal orientation, convection always occurs due to thermally and/or solutally buoyancy-driven flow through a density gradient with interactions with a gravitational acceleration on earth. In the vertical orientation, the convection can be suppressed if the ampoule is held in the convectively stabilizing position, with the source on a bottom and the crystal on a top region. This case corresponds to the diffusion-dominant mode over the convection. For the system under consideration in this study is based on the Hg_2Cl_2(A)-N_2(B) system where the molecular weight of component A is much greater than that of B, the solutally buoyancy driven-convection is predominated. As discussed before, with the crystal on the top position, the convective effects are reduced to one-fifth, and the convection is comparable to the diffusion or has little effect on the mass transport during the PVT. Fig. 4 shows the effects of the temperature difference between the source and the crystal on the interfacial distribution of growth rates along the y-direction for the crystal surface for a horizontal ampoule of aspect ratio 5, with a linear wall temperature profile between $T_s = 378.5^oC$ and $T_c = 358.1^oC$. Fig. 4 is based on the same parameters as in Fig. 2 with $\Delta T = 12.4$ K except for $T_s = 378.5^oC$, i.e. $\Delta T = 20.4$ K. As the temperature difference is increased form $\Delta T = 12.4$ K up to 20.4 K, i.e. by a factor of 1.64, the corresponding maximum rate for $g_y = 1\ g_0$ is enhanced by a factor of 1.71, indicating the temperature difference is directly and intimately linear to the growth rate. Moreover, the corresponding maximum rate for $g_y = 0.1\ g_0$ is enhanced by a factor of 1.33. Therefore, the effect of the temperature difference is more significant for $g_y = 1\ g_0$ than for $g_y = 0.1\ g_0$ at the same aspect ratio of 5. Note the conditions for Figs. 3 and 4 are unchanged except for the temperature difference of 20.4 K and aspect ratio of 5 in Fig. 4. As shown in Figs. 3 and 4, for the vertical orientation $g_y = 1\ g_0$, when the temperature difference is increased from 12.4 K to 20.4 K with increasing the aspect ratio from 2 to 5, the corresponding maximum rate is reduced by a factor of 0.49. On the other hand, for the horizontal orientation $g_x = 0.1\ g_0$, when the temperature difference is increased from 12.4 K to 20.4 K with increasing the aspect ratio from 2 to 5, the corresponding maximum rate is reduced by a factor of 0.26. These findings support that in a tenth gravitational level, the growth rate can be varied by altering the aspect ratio of ampoule or the temperature difference between the source and the crystal. As shown in Figs. 2 through 4, small non-uniformities in the growth rates occur in the gravity level of $g_y = 0.1\ g_0$, which stem from the recirculation of the component B in front of the crystal.

Fig. 5 shows the effects of molecular weight M_B on interfacial distribution of growth rates for a horizontal ampoule of aspect ratio 5, a linear wall temperature profile between $T_s = 378.5^{\circ}C$ and $T_c = 358.1^{\circ}C$ and $g_y = 1g_0$. To examine the effects of thermo-physical property of the molecular weight of B, MB, the MB in a body force term in Eq. (2) is fixed as 28.02 g/gmole and thus, the effects of solutal convection due to the solutal density gradient could be assumed to be negligible. The effects of thermo-physical properties on the growth rate when varying M_B in a horizontal orientation and aspect ratio of 5 and $T_s = 378.5^{\circ}C$ with $\Delta T = 20.4$ K are reflected through the binary diffusivity coefficient, D_{AB}. In other words,

$$D_{AB} \sim \sqrt{\left(\frac{1}{M_A} + \frac{1}{M_B}\right)}.$$

As the molecular weight of B is increased, i.e., approaches that of the crystallizing material A, the growth rate decreases sharply for $2 \le M_B \le 50$, and decreases much slightly for the molecular weight of B closer to that of the crystallizing material A, i.e., for $50 \le M_B \le 472$. One can see that when the molecular weight of A is much greater than that of B, the effects of the thermo-physical property become important. It is concluded that when the molecular weights of the two components are comparable and same, the thermo-physical properties have little effects on the crystal growth rate.

Fig. 6 shows the results of varying M_B in a horizontal system with Ar = 5 and $\Delta T = 20.4$ K on the growth rate, which are reflected in body force term in Eq. (2) with a fixed binary diffusivity coefficient in order to eliminate the effects of thermo-physical properties on the growth rate. Fig. 6 is associated with the effects of solutal convection on the growth rate. The growth rate decreases with increasing the molecular weight of B. Note only thermal convection occurs when a molecular weight of B is set equal to that of the component A, Hg_2Cl_2 at

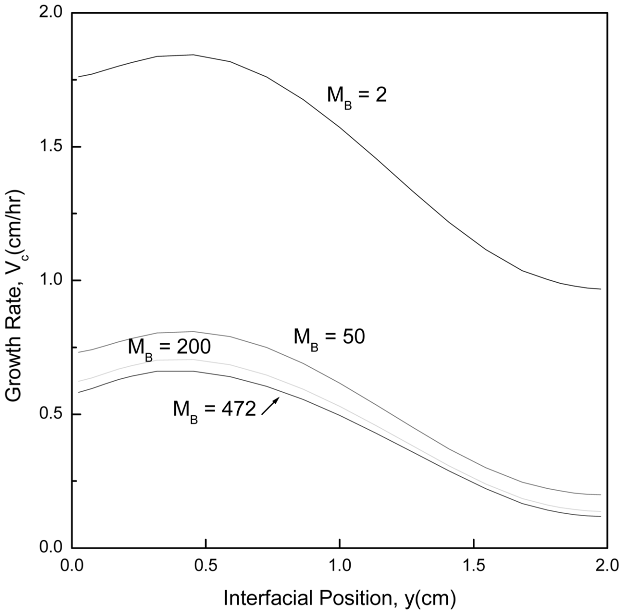

Fig. 5. Effects of molecular weight M_B on interfacial distribution of growth rates for a horizontal ampoule of aspect ratio 5, a linear wall temperature profile between $T_s = 378.5^{\circ}C$ and $T_c = 358.1^{\circ}C$ and $g_y = 1g_0$. A molecular weight M_B in a body force term is fixed as 28.02 g/gmole.

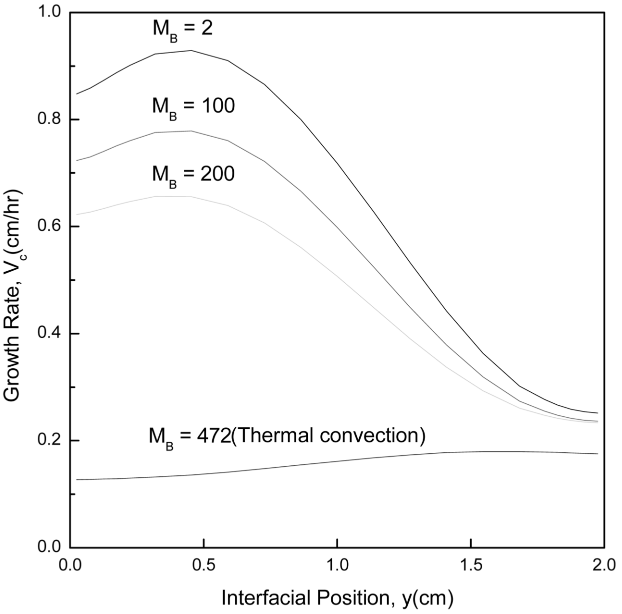

Fig. 6. Influence of solutal convection through molecular weight, M_B on the crystal growth rates of Hg_2Cl_2, with a fixed binary diffusivity coefficient. Solutal convection is reflected through solutally buoyancy in a body force term.

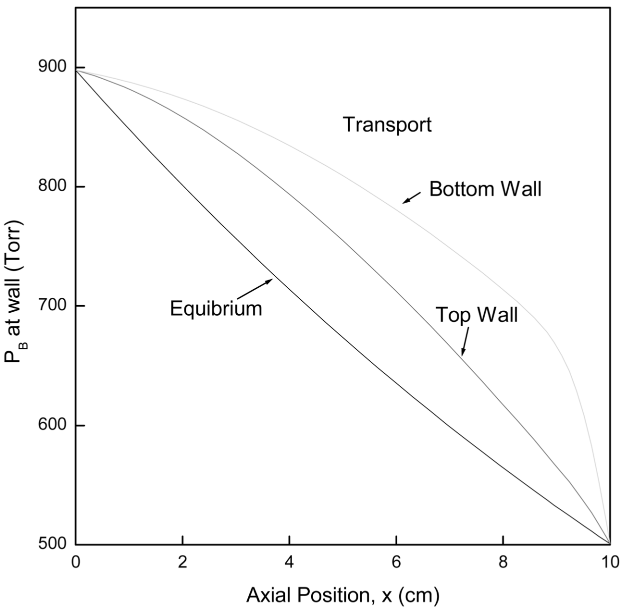

Fig. 7. Axial distribution of partial pressure of component A at the walls resulting from diffusive-convective transport for aspect ratio 5 and a linear wall temperature profile between $T_s = 378.5^oC$ and $T_c = 358.1^oC$ and $g_x = 1g_0$. The equilibrium vapor pressure profile shown for comparisons corresponds to the linear wall temperature distribution.

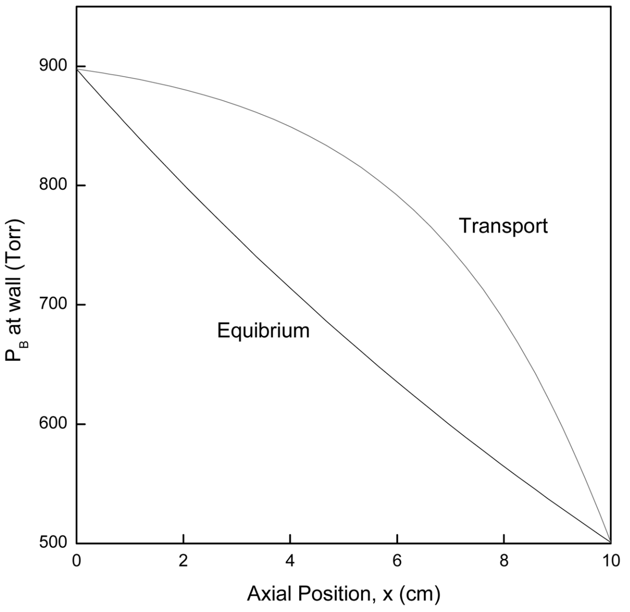

Fig. 8. Axial distribution of partial pressure of component A at the walls resulting from purely diffusive transport for aspect ratio 5 and a linear wall temperature profile between $T_s = 378.5^oC$ and $T_c = 358.1^oC$ and $g_x = 1g_0$.

density term in Eq. (2), i.e., the solutal convection would be assumed to be negligible. In other words, only when the two components have the molecular weights equal or very close to each other, the thermally buoyancy-driven convection is predominant over the solutally buoyancy-driven convection. The effects of solutal convection on the growth rate are much greater than those of thermal convection by a factor of 4~6 for $2 \leq M_B \leq 200$. For $2 \leq M_B \leq 200$, the asymmetry is enhanced as the difference between the molecular weights of the two components is increased. For the system of thermal convection with $M_B = 472$ g/g-mole, the uniformity in the growth rate is improved compared to solutal convection.

Fig. 7 shows the axial distribution of partial pressure of component A at the walls resulting from diffusive-convective transport for aspect ratio 5 and a linear wall temperature profile between $T_s = 378.5^oC$ and $T_c = 358.1^oC$ and $g_x = 1g_0$. One compares the equilibrium vapor pressure profile with the partial pressure of component A at the top and the bottom walls due to the diffusive-convective transport for the same system with for aspect ratio 5 and a linear wall temperature profile between $T_s = 378.5^oC$ and $T_c = 358.1^oC$ and $g_x = 1g_0$. As shown in Fig. 7, one can see that the component A of Hg_2Cl_2 vapor is in a super-saturation state in the vapor phase through the ampoule so that undesirable parasitic nucleation would occur at the walls during the mass transport. This happening is a very important concern for the crystal growers so that in actual experiments a nonlinear temperature profile with a hump pattern is used much than a linear temperature profile. Back to Figs. 2 and 4, the growth rates near the bottom wall are much greater than the top wall, which indicates the diffusive-convection flow structure with the counter-clockwise sense of rotation near the crystal region. This is consistent with the result that the partial pressure of component A near at the bottom wall is greater than that the top wall, as shown in Fig. 7. Note the equilibrium vapor pressure of component A, $P_A(T)$ is obtained from Eq. (8). Fig. 8 shows the axial distribution of partial pressure of component A at the walls resulting from purely diffusive transport for aspect ratio 5 and a linear wall temperature profile between $T_s = 378.5^oC$ and $T_c = 358.1^oC$ and $g_x = 1g_0$. Fig. 8 is in the same system except for the purely diffusive transport. Similar results as done in Fig. 7 are obtained from the purely diffusive transport, as shown in Fig. 8 in a viewpoint of vapor super-saturation in the vapor phase throughout the ampoule. Therefore, two cases of both diffusive convective and purely diffusive transport with a linear temperature profile are met with occurrences of parasitic nucleation at the ampoule walls so that a linear temperature profile would be rarely utilized in actual experiments.

As shown in Fig. 9, the growth rate (V_c, cm/hr) is first

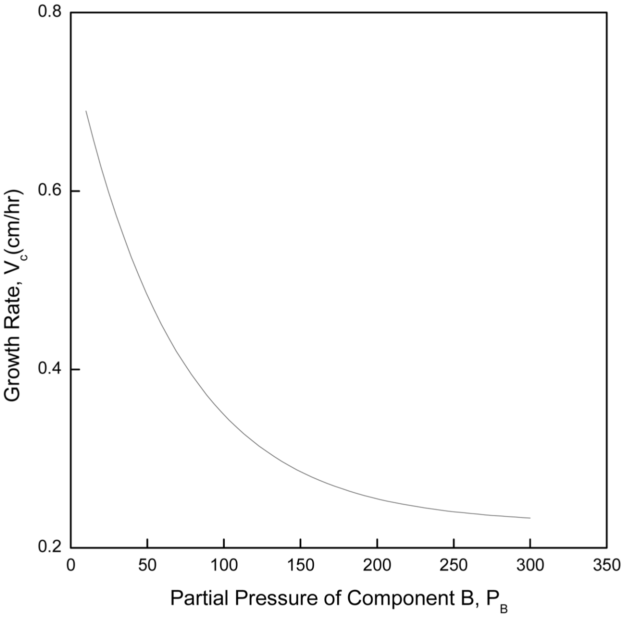

Fig. 9. Effects of partial pressure of component B, P_B (Torr) on the crystal growth rates of Hg_2Cl_2 for 10 Torr ≤ P_B ≤ 300 Torr, Ar = 5 and a linear wall temperature profile between $T_s = 378.5^{\circ}C$ and $T_c = 358.1^{\circ}C$ and $g_x = 1g_0$.

order exponentially decayed with P_B (Torr) for the range of 10 Torr ≤ P_B ≤ 200 Torr: $V_c = 0.22724 + 0.53596\exp(-P_B/67.60766)$. For 10 Torr ≤ P_B ≤ 50 Torr, the rate is decreased significantly and for 50 Torr ≤ P_B ≤ 200 Torr, reduced smoothly. Eventually the diffusive-convection transport approaches the diffusive transport. It is associated with the effects of smaller binary diffusivity coefficients on the growth rates due to higher total pressures: D_{AB}~$(1/P_T)$, where P_T is the total pressure throughout the ampoule. One can see in Fig. 10 that the maximum growth rates appear in the neighborhood of y = 0.5, and as the partial pressure of component B is decreased, the maximum growth rate increases for the range of the partial pressures of B under consideration. In particular, decreasing of P_B from 300 Torr to 100 Torr, i.e., by a factor of 0.33 gives the increasing of the growth rate from 0.33 cm/hr to 0.68 cm/hr, i.e., by a factor of 2.

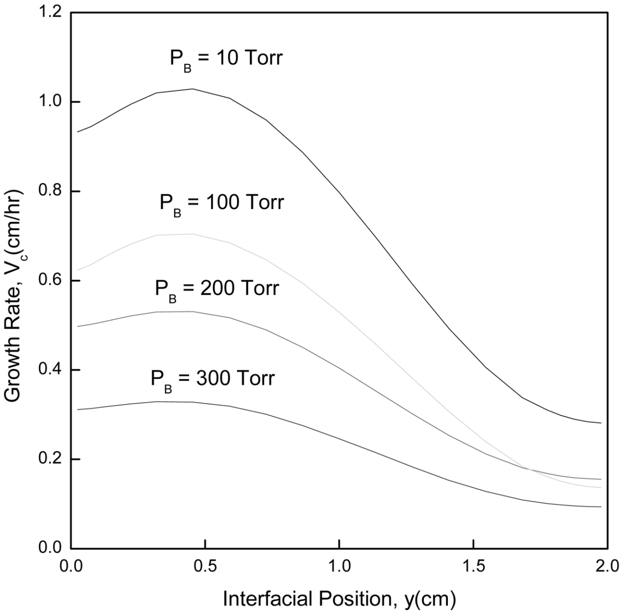

Fig. 10. Effects of partial pressure of component B, P_B (Torr) on the interfacial distribution of growth rates of Hg_2Cl_2 along the y-direction of the crystal surface for 10 Torr ≤ P_B ≤ 300 Torr, corresponding to Fig. 9.

4. Conclusions

For typical governing dimensionless parameters of Ar = 5, Pr = 1.16, Le = 0.14, Pe = 3.57, Cv = 1.02, $Gr_s = 2.65 \times 10^6$, the effects of thermo physical properties such as a molecular weight, a binary diffusivity coefficient, a partial pressure of component B on solutally buoyancy-driven convection (solutal Grashof number $Gr_s = 2.65 \times 10^6$) are theoretically investigated for further understanding and insight into an essence of solutal convection occurring in the vapor phase during the physical vapor transport of a Hg_2Cl_2-N_2 system. It is important that the solutal convection enhances the overall mass transport of component A, which is directly and linearly proportional to the growth rate, but generates much both the non-uniformity and asymmetry in the growth rate. It is found that solutal convection is suppressed for a tenth reduction in gravitational acceleration, $0.1g_0$ and altering the orientation of the ampoule is more useful than resorting to the low gravity environment of $0.1g_0$. For crystal growth parameters under consideration, uniformity in the growth rate is much improved by either utilizing a vertical orientation or setting the molecular weight of component B equal to that of the crystallizing material, component A. It is also concluded that maximum growth rates appear in the neighborhood of y = 0.5 for the horizontal system regardless of the gravitational accelerations down to $10^{-1}g_0$. When the molecular weight of A is much greater than that of B, the effects of the thermo-physical property become important. If the molecular weights of the two components are comparable and same, the thermo-physical properties have little effects on the growth rate. The growth rate (V_c, cm/hr) is first order exponentially decayed with P_B (Torr) for the range of 10 Torr ≤ P_B ≤ 200 Torr: $V_c = 0.22724 + 0.53596\exp(-P_B/67.60766)$. For 10 Torr ≤ P_B ≤ 50 Torr, the rate is decreased significantly and for 50 Torr ≤ P_B ≤ 200 Torr, reduced smoothly. Eventually the diffusive-convection transport approaches the diffusive transport. It is associated with the effects of smaller binary diffusivity coefficients on the growth rates due to higher total pressures.

Acknowledgement

The authors wish to appreciate the financial support provided by the Hannam University through a research program entitled “Hannam University Hak-sul-yeonku-chosungbi” (starting from April 1, 2010 through March 31, 2011).

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