Numerical Computations on Heat Transfer Characteristics in a Cavity Swept by Hydrate Slurry Transported with Visco-Elastic Fluid

**Hiroshi Suzuki, **Sayaka Yamada, *Ryoichi Nakamura, ***Yoshiyuki Komoda and ***Hiromoto Usui*
**Graduaste School of Science and Technology, Kobe University*
1-1 Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan
*** Mechanical Engineering Research Laboratory, Kobe Steel, Ltd.,*
1-5-5 Takatuka-dai, Nishi-ku, Kobe 651-2271, Japan
****Department of Chemical Science and Engineering, Kobe University*
1-1 Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan

Abstract

A two dimensional numerical study has been performed to investigate on heat transfer of hydrate slurry transported by a visco-elastic fluid in a cavity. In order to investigate the optimum geometric parameter, the effects of the rib height and the cavity length were changed in three steps, respectively. From the results, it is found that hydrate particles dispersed with Newtonian fluid (water) flow over the cavity without penetration. On the other hand, hydrate particles dispersed with visco-elastic fluid are observed effectively to penetrate into the cavity and sweep the bottom of cavity by Barus effect. Though the local heat transfer coefficient decreases in the downstream region of the cavity due to the development of thermal boundary layer, the mean Nusselt number on the cavity bottom in this visco-elastic dispersion medium cases becomes higher than that for water cases in corresponding cavity length. It was also found that heat transfer characteristics were significantly affected by cavity length for both dispersion medium cases. It is concluded that the visco-elastic dispersion medium causes effective heat transfer improvement in a cavity and that there exists the optimum geometry for the heat transfer augmentation in a cavity by using Barus effect.

Key words : Hydrate Slurry, Barus Effect, Visco-elastric Fluid, Convective Heat Transfer, Cavity

Introduction

Process intensification and miniaturization of heat devices becomes important for global sustainability. Latent heat transportation system is one of items for realizing them, because it can transport high density of heat and sustain the temperature of fluid. The authors reported some experimental and numerical studies on the latent heat transportation system with hydrate slurries. Some materials form hydrate in water, which has high latent heat and can be easily treated. However, hydrate slurries generally have high viscosity and increase the pumping power increase. Suzuki et al. (2006a) reported the friction coefficient of trimethylolethane clathrate hydrate slurry can be effectively reduced with surfactant drag-reduction technology. They showed the friction coefficient becomes a half of that in the case of water. However, surfactants additive also causes heat transfer reduction as reported in the previous study (Indartono et al., 2006). So, some heat transfer augmentation methods are required for heat transportation applications.

Until now, many techniques on heat transfer enhancement have been suggested. Among them, rib-shaped promoters mounted on heat transfer surface are often used in order to increase heat transfer area. These kinds of devices are expected to perform a turbulence promoter (Kim et al., 1983). However, the heat transfer in a cavity between ribs is normally reduced.

In our previous study (Suzuki et al., 2002), a novel technique using the Barus effect of visco-elastic fluid for heat transfer augmentation was suggested. Nakamura et al. (2006b) reported this kind of techniques becomes effective in low Reynolds number region. Hydrate slurries treated with drag-reducing surfactants have strong visco-elasticity. Regarded to this, Nakamura et al. (2006a) also found that this kind of heat transfer enhancement method is effective for hydrate slurries dispersed by visco-elastic fluid. However, they reported the results under limited geometric conditions.

The purpose of the present numerically study is to investigate the optimum geometric condition for the heat transfer enhancement technique with hydrate slurry transported by a visco-elastic fluid. The visco-elasticity of fluid was calculated by using Giesekus model (Giesekus, 1982). Model parameters tuned for the surfactant solution by Suzuki et al. (2006b) are adopted. The effects of cavity length and rib height will be discussed.

2. Computational Procedures

The computation domain is shown in Figure1. In this study, the width of the wider flow path, W [m], and the length, B [m], of ribs mounted in one side of the flow path are fixed at 40mm and 1m, respectively. The rib height, H [m], and the cavity length, L[m], were changed in three steps, respectively; H=10, 15 and 20mm and L=0.05, 0.1 and 0.2m. x [m] and y [m] are the streamwise and normal coordinates, respectively, and its origin is set at the cavity upstream bottom.

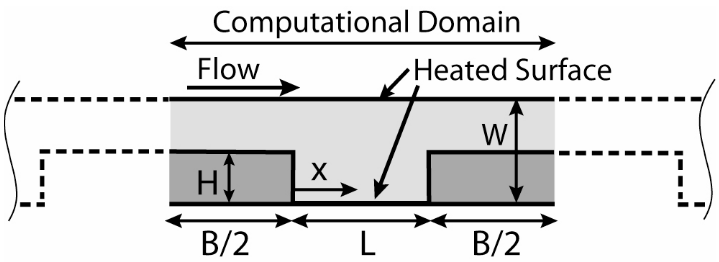

Figure 1 Computational Domain

The governing equation set includes two-dimensional continuity, momentum, and energy equations. In the Cauchy's equation set for momentum equations, stress components is given by Newton's law for water flow. The transport equation on hydrate particle concentration is assumed to have no molecular diffusion term. Phase change between the solid and liquid phases was estimated by temperature recovery method. According to this method, the quantity of heat with temperature rising removed by melting heat in computational cell. The visco-elasticity of fluid was calculated by using Giesekus model including retardation time. The model parameters used in this study were set as modeling surfactant solution flow tuned by Suzuki et al (2006b). They are tabulated in Table 1. Finite differencing method was applied to solve these equations. The central differencing is used for diffusion term, QUICK for the convection term, SIMPLE for the pressure term and implicit method for time marching.

Rib Reynolds number, Re_H, defined with rib height, bulk mean velocity in the narrow flow path, U_m[m・s^{-1}] and water kinematic viscosity was kept constant at 100. Under this condition, the narrow flow path Weissenberg number, We_{W-H}, defined with the width of narrow plow path, bulk mean velocity in the narrow flow path and relaxation time ranged from 0.025 to 0.0333 as tabulated in Table 2.

Table 1 Model Parameter

Relaxation Time, λ	0.1s	Retardation Time, λ_R	0.002086s
Mobility Parameter, α	0.18	Solute Zero Viscosity, η_P	0.00447Pa・s

Table 2 Computational flow conditions

H [mm] / *L* [m]	*H/W*			*L/H*		
	10	15	20	10	15	20
0.05	0.25	0.375	0.5	5	3.33	2.5
0.1	0.25	0.375	0.5	10	6.66	5
0.2	0.25	0.375	0.5	20	13.3	10
H[mm] / *L*[m]	Re_H			$We_{W\text{-}H}$ x 10^2		
	10	15	20	10	15	20
0.05	100	100	100	3.33	2.67	2.50
0.1	100	100	100	3.33	2.67	2.50
0.2	100	100	100	3.33	2.67	2.50

No-slip condition was assumed at a solid wall and the solid wall was heated by constant heat flux condition, 20,000 $W \cdot m^{-2}$. For the comparison, the cases without hydrate particles were also computed when L/H=5. In these cases, heat flux was set at 750 $W \cdot m^{-2}$. A periodic condition was applied at the inlet and outlet of the domain for momentum and energy equations. For energy equation, the temperature profile at inlet was assumed only to have the difference of the bulk temperature from that at the outlet. Then, the temperature field at the inlet was determined as the bulk temperature increase was subtracted from that at the outlet. For hydrate concentration, inlet condition is set at 5wt% and the streamwise gradient of hydrate concentration is assumed to be zero at outlet. For comparison, water flow cases were also computed with the same conditions. With these conditions, steady conversion was obtained for all cases treated in the present study.

3. Results and Discussion

3.1 Streamlines and TME concentration

Figure 2 shows streamlines in cases when L/W=2.5, respectively. Streamline characteristics were discussed in detail by Suzuki et al. (2006b). Then, a brief review is only given here.

From these figures, it is found for water cases that the flow separates from the top corner of the backward-facing step and no penetration into the bottom wall is observed when the cavity length is small. Then, recirculating region is formed in the cavity. This recirculating region becomes wider in the cavity with increase of H/W. On the other hand, hydrate particles slurries are penetrated into the cavity by Barus effect when dispersion medium has visco-elasticity. As H/W increases, the flow rate penetrating into the cavity becomes larger. Then, high heat transfer rate can be expected.

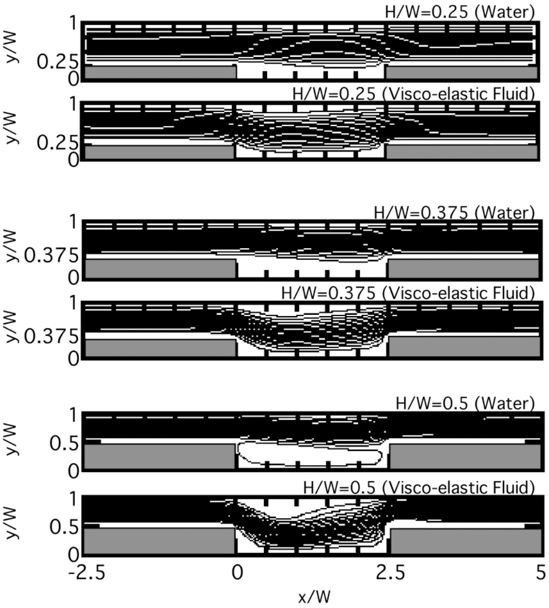

Figure 2 Streamlines

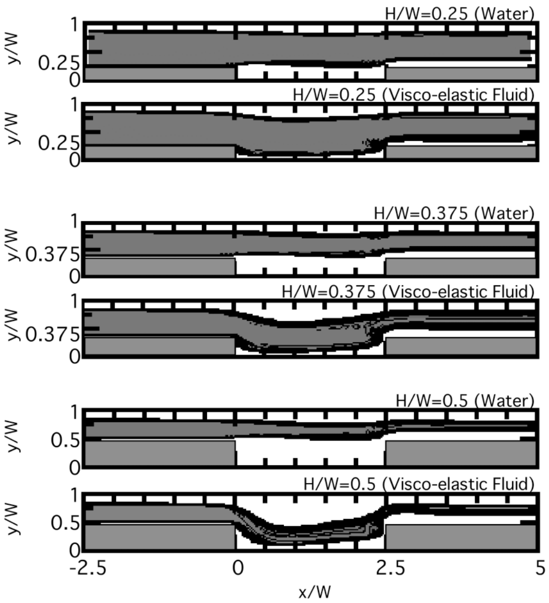

Figure 3 TME Concentration Contours

Figure 3 shows TME concentration contours in cases of L/W=2.5. In this figure, high concentration region is designated as a shaded part.

From this figure, it is found that the hydrate concentration is sharply changed at the edge of the shaded part in all cases. This indicates temperature change sharply at the edge and flat distribution realized in the core region of shaded part.

For cases of water dispersion medium, it is found that hydrate particles is not observed in the cavity. This corresponds to the fact that no flow penetration is observed as mentioned above. On the other hand, hydrate particle slurries effectively penetrates into the cavity by Barus effect of visco-elastic dispersion medium. This is caused by the flow penetration into the bottom of cavity. As H/W increases, the TME concentrated region becomes small. This makes hydrate particle effectively melt and brings high heat transfer with increase of H/W.

3.2 Heat transfer characteristics

Figure 4 shows local Nusselt number, Nu[-], distribution on the bottom wall of the cavity defined with rib height, H, and bulk temperature of each cross section in cases of L/W=2.5. In the figure, the results for the cases without hydrate particles for comparison.

From this figure, it is found that the local Nusselt number in the cases of water dispersion medium takes the maximum value at the end of the cavity. In these cases, flow separates at the top corner of the upstream of the cavity and reattached to the top corner of the downstream of the cavity. For the corresponding case without hydrate particles, the local Nusselt number takes small values even at the cavity end. In the cases with hydrate particles, the temperature of the wake quickly decreases because the temperature of hydrate core is kept low. Then, the flow reattaching to the top corner of the downstream of the cavity has low temperature. This is considered to cause the maximum heat transfer at the end of cavity. On the other hand, the wake temperature remains high in the case without hydrate particles. Then, the local Nusselt number takes a lower value there compared with the corresponding case with hydrate particles.

Turning attention to the cases of visco-elastic dispersion medium, it is found that the local Nusselt number shows a marked peak around x/W=1 for each case. This corresponds to the flow approach to the bottom wall of the cavity. This flow approaching point is not so significantly affected by the rib height as shown in Fig. 2. At the same position, a peak is observed in the case without hydrate particles. However, its magnitude is much smaller than that of the case with hydrate particles. This is caused by the temperature sustainability of hydrate slurry.

Finally, Mean Nusselt number, Nu_m[-], shows in Figure 5. In this figure, the results for the cases without hydrate particles when H/W=0.5 and L/W=2.5 are also plotted.

From this figure, it is found that the mean Nusselt number in the cases of visco-elastic dispersion medium takes higher values that those of water dispersion cases in any cavity length. Mean Nusselt number becomes larger as H/W increases. This corresponds to the fact that flow rate penetrating into the cavity becomes larger with H/W. From the comparison with the cases without hydrate particles, it is found that hydrate addition causes almost twice heat transfer rate. This is consistent with the report by Indartono et al.(2006).

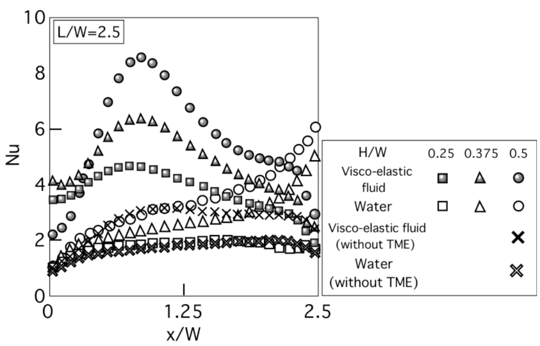

Figure 4 Local Nusselt number distributions

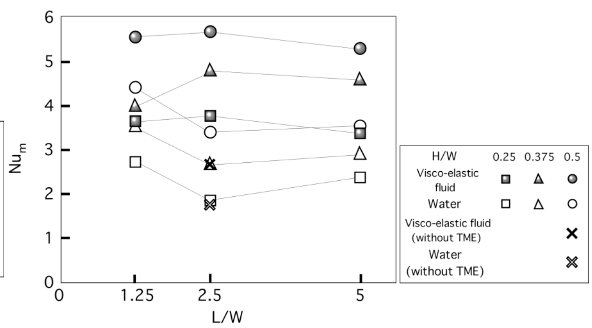

Figure 5 Mean Nusselt number

4 . Conclusions

In this study, the effects of the rib height and the cavity length on the heat transfer characteristics in a cavity were investigated for the heat transfer augmentation with visco-elastic fluid. From the results, it is found that hydrate particles dispersed with Newtonian fluid (water) flow over the cavity without penetration. On the other hand, hydrate particles dispersed with visco-elastic fluid are observed effectively to penetrate into the cavity and sweep the bottom of cavity by Barus effect. Though the local heat transfer coefficient decreases in the downstream region of the cavity due to the development of thermal boundary layer, the mean Nusselt number on the cavity bottom in this visco-elastic dispersion medium cases becomes higher than that for water cases in corresponding cavity length. It was also found that heat transfer characteristics were significantly affected by cavity length for both dispersion medium cases. It is concluded that the visco-elastic dispersion medium causes effective heat transfer improvement in a cavity and that there exists the optimum geometry for the heat transfer augmentation in a cavity by using Barus effect.

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